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Determining the Optimal Reserve Capacity of a Microgrid Based on the Probabilistic Analysis of Grid-connection in Market Environment

시장환경에서 마이크로그리드 계통연계 상태의 확률론적 분석에 기반한 최적 예비력 스케쥴링에 관한 연구

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Abstract

Determining the Optimal Reserve Capacity of a Microgrid Based on the Probabilistic Analysis of Grid-connection in Market Environment

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Microgrid can be a useful entity to support stable and efficient operation of power systems with large-scale penetration of distributed generators, such as wind generators, energy storage systems, and combined heat and power plant. One major characteristics of microgrid is that it could take an island operation and maintain its reliable power supply if an accident occurred in the main grid. However, microgrid operator (MGO) cannot help taking some special action like load shedding during the island operation, since its generation capability has a limit. Therefore, MGO has to take this island operation into account when it make a plan for its own energy resources. Actually many prior researches about microgrid operation include reserve power scheduling in preparation for the uncertain islanding event.

This dissertation analyses the risk of microgrid island operation, and describes the method that enables MGO to reflect this probabilistically into its operating cost when it makes a plan for the energy resources. In order to this, an islanding event of the microgrid is interpreted as a transaction suspension, and microgrid islanding rule is defined in the form of market rule to clarify the responsibility distribution of a contract breach in a market. To quantitatively examine the influence of market rule, different two microgrid islanding rules are proposed based on the Power Exchange for Frequency Control (PXFC) market, which was devised by M. Ilic *et al*. Postulating these two rules, the risk of microgrid island operation is examined. In other words, the triggering condition of islanding event is mathematically formulated, and microgrid islanding probability (MIP), which represents the probability of being in the islanded state during a unit time, is proposed and calculated. Utilizing the proposed MIP index, an optimization problem is constructed. The objective function is expected value of daily operating cost of microgrid, which include the risk of microgrid island operation, and the decision variable is the purchase capacity of reserve band in PXFC market. The optimization problem is solved and simulated with the market information of the PJM electricity market. The effectiveness of the proposed reserve scheduling method in terms of operating cost is investigated using simulations, where the proposed method and two further methods are applied to microgrids with different generation capabilities. Also simulation results of MIP analysis show that microgrid island operation has some hysteresis characteristics. Utilizing the proposed method, MGO can schedule its reserve power corresponding the market and grid conditions.

Keywords : Microgrid, Island Operation, Bernoulli Trial, Reserve Capacity, Cost Minimization, Power System Operation

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Contents

List of Tables

List of Figures

Nomenclature

N_{stage}	**Number of time stages in a day**
N_{step}	**Number of time stages in a day**
BD_i	**Requested reserve band capacity during the *i*-th stage.**
C_{TOT}	**Expected value of total operating cost.**
CG_i	**Grid-connected operating cost during the *i*-th stage.**
CI_i	**Islanded operating cost during the *i*-th stage.**
EG_i	**Energy supply cost in the grid-connected mode during the *i*-th stage.**
RG_i	**Reserve supply cost in the grid-connected mode during the *i*-th stage.**
G_i	**Internal generation cost during the *i*-th stage.**
M_i	**Power import/export cost benefit during the *i*-th stage.**
EI_i	**Energy supply cost in the islanded mode during the *i*-th stage.**
RI_i	**Reconnection cost in the islanded mode during the *i*-th stage.**
LS_i	**Load shedding cost in the islanded mode during the *i*-th stage.**
x_i	**Forcasted internal demand during the *i*-th stage.**
$x_i^{G,int}$	**Internally generated power in the grid-connected mode during the *i*-th stage.**
$x_i^{I,int}$	**Internally generated power in the islanded mode during the *i*-th stage.**

x_i^{ext} **Imported/exported power from/to the main grid through the energy market during the *i*-th stage.**

x_i^{LS} **Load shedding quantity during the *i*-th stage.**

k_i **Microgrid islanding probability (MIP) during the *i*-th stage.**

p_{ij} **Probability of islanding during the *i*-th stage.**

q_{ij} **Probability of maintaining the grid-connected state during the *i*-th stage.**

X_{ij} **Islanding state during the *i*-th stage.**

X_{i0+} **Islanding state immediately prior to the binomial experiment during the first step of the *i*-th stage.**

Chapter 1. Introduction

1.1 Background

The penetration of distributed generators (DGs) in low-voltage distribution system is increasing worldwide. Improvements in the efficiency of small generators, as well as in technologies for combining electricity with other types of energy, such as heat, can enable DGs to be similarly economic as traditional large-scale generators [1]. However, controlling a large number of DGs poses new challenges for stable and efficient operation of power systems. A microgrid is an entity consisting of small subsystems, such as generators, loads, and energy storage systems (ESSs). There is a microgrid operator (MGO) as in Figure 1.1, who controls these distributed resources and determines the market participation of the microgrid. MGO can coordinate these distributed energy resources in a decentralized way, thereby reducing the computational costs for control incurred by the system operator (SO), and enabling more efficient operation [1]–[3]. Normally MGO tries to maintain its grid-connection to the main grid, to operate its system reliably by utilizing some ancillary service such as frequency control that upper operator provides, and to get economic benefit by providing electricity to or receiving electricity from the market. However, it can also operate in an islanded mode; i.e., disconnected from the main grid. For example, if a large accident occurs in the main grid, MGO could cut the connection and operate in the islanded mode to protect its system. During the islanded operation, the microgrid must meet demand and maintain proper levels of reliability with its own balancing capability.

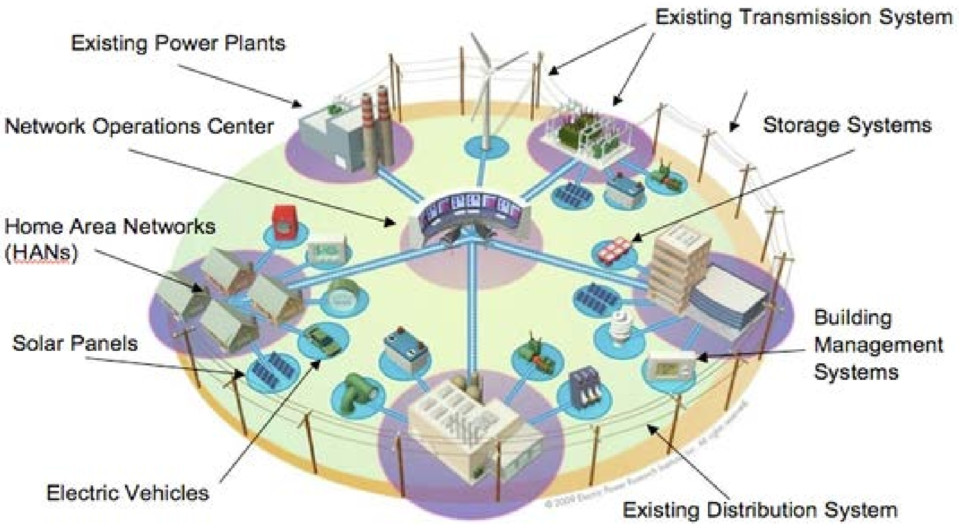

Figure 1.1 An example of the typical microgrid system [28]

1.2 Previous Researches

Microgrid is more independent and decentrally operated than traditional distribution network and there has been many researches about it. Since the first reports about microgrids appeared in the 1990s, the basic operation concept and implementation methods were established in the early 2000s. A variety of microgrid system analysis method and operating scheme have appeared, and they can be split into two groups: physical grid analysis and economical operation analysis.

For the physical grid analysis, [4] and [5] describe system modeling and stability analysis for the microgrid. Specifically, a small-signal model of an islanded microgrid, consisting of asynchronous generator based wind turbine, synchronous diesel generator and power electronic based ESS, was proposed to investigate its dynamic stability [4]. And the factors influencing the stability of a microgrid, both in grid-connected mode and islanded mode, and several ways of improving the stability were investigated [5]. There have also been analyses of control schemes for the DGs and ESSs, which maintain the frequency and voltage of an islanded microgrid [6]–[8]. For this, grid code for operating a microgrid stably, such as voltage/frequency regulation and voltage/frequency-droop characteristic, were investigated and real and reactive power management strategies for a microgrid was proposed. On the contrary to this, [9] and [10] investigated the technical possibility of providing frequency control reserves to the main grid by aggregating multiple microgrids.

For the economical operation analysis, various models and methods to minimize the operating costs were investigated when a microgrid is included in the traditional economic dispatch or unit commitment models. [9] assumed a microgrid that supply not only electricity demand but also local heat demand, and proposed a dispatch scheme for minimizing the fuel consumption of it. And the optimal scheduling of a microgrid considering island operation and market participation were investigated [10]–[12]. [10] proposed an economic dispatch model for a microgrid that possessed additional reserve constraint for island operation, and [11] and [12] presented unit commitment models for minimizing the operating cost of a microgrid that has to prepare for an uncertain island operation. There is also a research about economic evaluation of the microgrid's market participation when the market environment and the bidding strategy of the microgrid change [13].

1.3 Objectives of the dissertation

As mentioned in the Section 1.2, most microgrid researches have been conducted into the islanded mode of a microgrid, which did not exist in the traditional power system operation researches. However, prior researches mainly deal with the coping method with the microgrid island operation, such as control scheme for stabilizing the grid and scheduling method that can mitigate the influence of islanding, and hardly deal with the specific triggering condition of the islanding event. Therefore, prior researches about economic analyses of microgrids cannot help indirectly expressing the chance of operating cost change from the uncertain islanding event by setting reliability or reserve constraint. Even these did not provide detailed quantitative method of setting the standard value of that constraint. Also prior researches do not consider the responsibility of unilateral trade suspension from an islanding event, but only consider the problem of energy supply in the microgrid, even though trading electricity in market is a legal contract between the MGO and market counterparty.

This dissertation is in the category of the microgrid economic operation analysis, and focuses on the probabilistic analysis that can reflect the uncertainty of island operation into the scheduling level. Making up for the problems of the previous researches, a microgrid islanding rule in the form of a market rule is proposed and the risk of microgrid islanding is studied based on this market rule. Utilizing these, MGO’s risk hedging strategy with uncertain island operation is formulated as an optimization problem, where the objective is to minimize the expected value of daily operating cost of a microgrid.

1.4 Overview of the dissertation

The remainder of the paper is structured as follows. In Section II, electricity market operation in multi-microgrid environment is studied. In other words, a proper market structure is introduced and postulated as a mandatory market in this dissertation: the Power Exchange for Frequency Control market that was devised by Ilic *et al.* [17]. An islanding event in this dissertation is analyzed in terms of the reserve band contract in the PXFC market, and the responsibility of the trade suspension from this islanding event is studied. In order to examine this quantitatively, two microgrid islanding rules are proposed as a penalty rule of the PXFC market: a simple rule (Microgrid Islanding Rule A) and a general rule (Microgrid Islanding Rule B).

Section III deals with the decision process of a microgrid operator (MGO) with Microgrid Islanding Rule A in PXFC market. MGO's operation strategy is formulated as an optimization problem, and composition of the objective function is examined in Section III. In order to reflect the risk of microgrid island operation into the cost function of the optimization problem, a probabilistic method based on the concept of microgrid islanding probability (MIP) is proposed. Using this method, the optimal reserve band capacity of a microgrid that minimize its operating cost can be calculated. The effectiveness of the proposed method within the PXFC market is investigated using simulations in Section IV. For this, proposed method is compared with two different methods that have similar reserve supply cost. Also the characteristics of MIP index and the relationship between MIP and reserve band capacity are examined.

Section V and VI deals with the MGO's operation strategy with Microgrid

Islanding Rule B. Like as Section III and IV, the optimal reserve band capacity of a microgrid that minimize its operating cost is calculated based on the probabilistic method and the effectiveness of the proposed method is investigated using simulations. Also the comparison between the proposed operation strategies with two different islanding rules is conducted. Lastly concluding remarks and future extensions are given in Section VII.

Chapter 2. Microgrid Operation and Market

2.1 Electricity Market in Microgrid Environment

Microgrid is different from traditional distribution system. Depending on the market and grid conditions, microgrid can take the role of either a generator or a demand, whereas traditional distribution system just maintain its position. Furthermore, utilizing the control of own DERs, microgrid can participate in not only energy market but also various ancillary service market where traditionally some generators has been only able to participate. Likewise the effects and contributions of the grid-connected microgrid to frequency regulation of the main grid have been addressed recently [13], [14], showing that a microgrid or an aggregation of multiple microgrids can perform the same functions as automatic generation control (AGC), and obtain economic benefit by providing ancillary services to the main grid. Also a method to allow a microgrid to support the same frequency control function indirectly through the market has been reported [15]. In conclusion, since microgrid can take more active role in the power system and market operation than traditional distribution system, power system consisting of multi-microgrid can be operated more efficiently in a new market environment. Figure 2.1 shows the difference between traditional power system and microgrid power system.

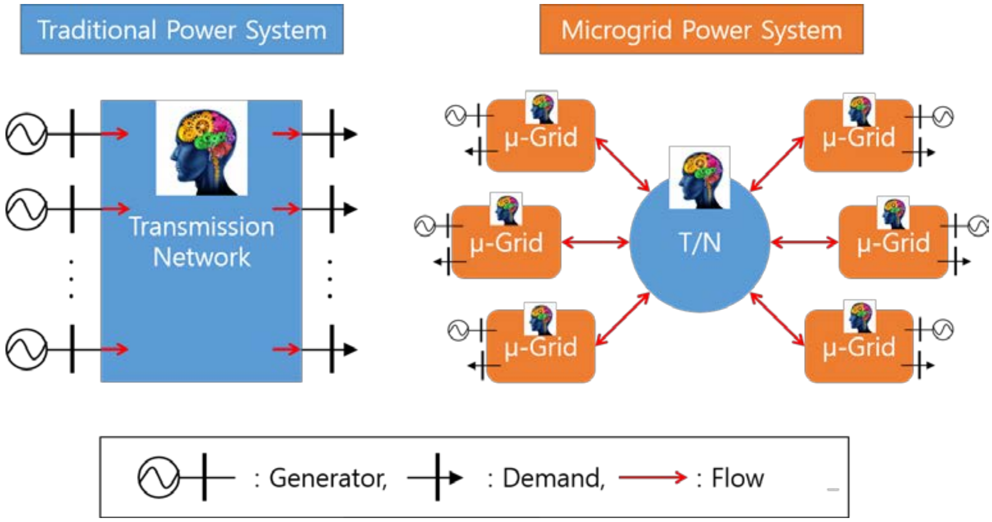

Figure 2.1 Operation scheme of traditional power system and power system consisting of multi-microgrid

2.2 Power Exchange for Frequency Control Market

Recent reports [17], [18] have suggested that participants in the operation of power systems, including generation companies and load-serving entities, should be prepared to pay compensation for frequency deviations, and reserve capacity for frequency control should be provided by the SO. As a result, various types of reserve market have been set up to assign reasonable responsibility to each participant [18]. For example, PJM imposes the cost of preparing an operating reserve in the form of an *ex ante* cost as well as the cost of a balancing settlement in the form of an *ex post* cost on load-serving entities [19]. However, existing reserve markets involve mainly adding obligation to the participants for secure power system operation. Moreover, this obligation might result in excessive reserve cost particularly when there is high penetration of non-dispatchable resources such as wind power [20]. In this respect, the PXFC market structure in [16], in which each participant make its own decision regarding the purchase quantity of reserve service considering the purchase cost and the risk of utilizing unreserved service, is adopted in this paper in order to foster competition and transparency in the market.

The PXFC market consists of two submarkets: an energy market for trading reference power, and a band market for preparing reserve capacity. The reserve capacity, which is the main topic of this work, is described as a frequency control band in the PXFC market. All the contracts are agreed on a daily basis, and they should satisfy two quantities as a function of time: the anticipated power supply/demand, and the frequency control band corresponding to the estimate of the maximum deviation from the anticipated value. Figure 2.2 shows a typical contract in the PXFC market between a participant and the SO. The SO estimates the total frequency deviation in the system by considering the size of each of the participant's reserve bands and the correlation among the deviations of the participants. Based on this, AGC generators are employed and their purchase cost is distributed equally among all participants in proportion to the requested size of the frequency control band. Therefore, the participants who induce more uncertainty in the grid, such as wind generator and steel mill, will take more responsibility and pay more cost in the system frequency regulation than others.

If a microgrid appears in the PXFC market, the same process is applied to the microgrid. In other words, a microgrid should forecast its power shortage/surplus to determine the reference power in the energy market, and estimate the maximum deviation from the reference power to determine the required reserve. In this manner, the participants of the PXFC market, including microgrids, pay for imbalances in the form of an ex ante cost for the band, and take a more active role than in the frequency control of the entire power system.

In the PXFC market, frequency control can be implemented in a decentralized market-based scheme. In practice however, a form of sanction or penalty must be imposed on participants that violate a contract of the band market significantly and/or repeatedly [16]. This occurs when; e.g., a participant specifies a frequency control band that is narrower than necessary in order to save costs. Although definite rules of the penalty were not described in [16], various forms of these rules may be defined according to the properties of the power system, such as the required level of reliability, the system size and the droop characteristics of generators. For instance, if supply capability is much greater than demand, there may be sufficient reserve margin in the system so that the penalty in the form of pricing proportional to the violation would be sufficient for stable operation. However, if the reserve margin is only just maintained, or the system is vulnerable to disturbances such as line faults, then stronger measures must be taken to ensure the stability of the system, such as excluding violators from the grid connection for a period of time. In conclusion, there may be various types of penalty rules according to the system in question. The penalty rules proposed in this paper focus on excluding a participant from the system, particularly with islanded microgrids, which may operate independently during the disconnected state.

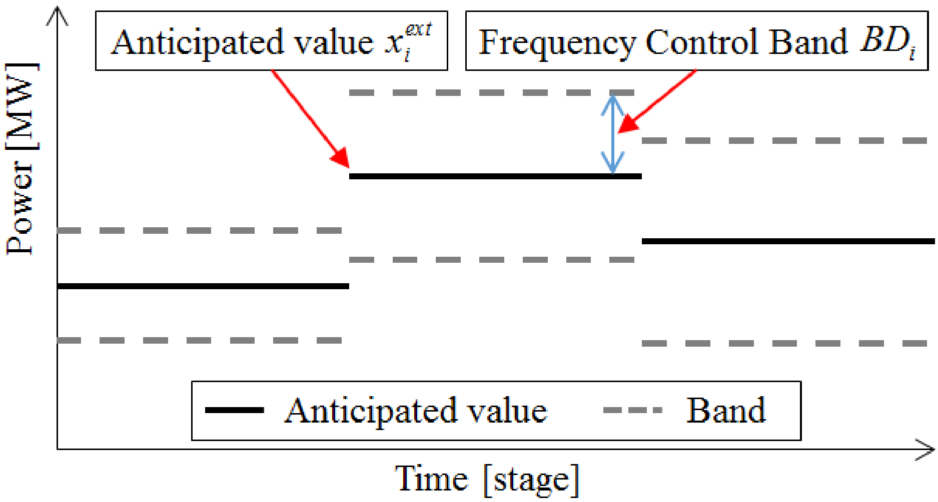

Figure 2.2 Typical structure of a contract in the PXFC market

2.3 Microgrid Islanding Rule A

Most reports of islanded microgrids have focused on methods to achieve stable operation of the microgrid when islanding occurs. Therefore islanding has been considered a contingency to be simulated to guarantee the so-called 'N-1' reliability criterion. In other words, in a unit commitment or economic dispatch problem, the MGO treats islanding as a constraint related to the required minimum reserve capacity [9] or the allowed maximum islanding duration [12]. In terms of the stable and efficient operation of a microgrid, however, it is more important to specify the conditions in which islanding is enforced and which party should take the responsibility for the losses incurred due to islanding. To describe these issues, a set of penalty rules for islanding should be included in the contract between the SO and an MGO in the PXFC environment. In this respect, this paper proposes two microgrid islanding rules: Rule A and Rule B, and analyses the risk of microgrid island operation based on these two rules. The Rule A is as follows:

Rule A-I: The occurrence of islanding depends only on the observance of a contract in the band market.

Rule A-II: Islanding occurs immediately when a deviation from the reference power exceeds the requested frequency control band.

Rule A-III: If islanding occurs during a given step of a stage, it lasts for the duration of the remaining steps of that stage, as well as the following next stage, after which the microgrid is reconnected to the main grid.

Rule A-IV: Transaction prohibition is the only penalty for islanding, and there are no additional penalties, such as imposition of a fine.

In Rule III, the step and the stage represent time units for the occurrence of islanding and the contract in the PXFC market, respectively; in the simulation part of this paper we assume that each stage consists of six steps, although other systems may use a different number.

These rules describe the entire process, from the occurrence of islanding to the reconnection of a microgrid to the main grid. Specifically, Rule I implies that the conditions for the occurrence of islanding are included in the contracts of the PXFC market and islanding results from a breach of a band contract. Thus, a microgrid that would like to participate in the energy market should comply with the contract to maintain the grid connection, and the SO has responsibility to ensure reliable operation of the main grid for the transactions among the participants who observe their contracts. Penalty Rules II and III clarify the duration of islanding. This is similar to the punishment in some stock markets, whereby a securities regulator suspends trading in stocks for a time to prevent a company from acting against the interests of investors or the public [21]. Furthermore, from the perspective of physical systems, a period of time is required to prepare resynchronization to the main grid, both in terms of the frequency and the voltage. This is similar to the constraint on the minimum downtime of a thermal unit in the unit commitment problem [22]. Thus, the necessary time for reconnection to the main grid is specified in Rule III.

Rule IV means that the cost for a breach of contract is indirectly reflected in the operating costs of the islanded microgrid, and this is the only penalty for the violation. This Rule IV prescribes the responsibility between MGO and SO about trade suspension of electricity from islanding. This kind of responsibility rule, which defines the indemnification for a breach of the contract, is necessary for not only electricity trade but also all kinds of future trading. However, the difficulty lies in estimating the damage caused by trade suspension. First, the extent of the damage is unclear in some places [29]-[30]. It could include the substitute-price of replacing a promised trade with a substitute trade, the surplus that the victim of breach would have enjoyed if the breaching party had performed, and the opportunity cost that the victim of breach would have enjoyed if he had signed the best alternative contract, but these are all imprecise. Also it is hard to find out who is responsible for the breach of contract. Sometimes both parties would be responsible for the breach, and the responsible party would be unclear if the breach is caused by some accident, e.g. natural disaster. For these reason, almost futures trading contracts include the matter of responsibility, and specify the party in charge and the compensation scale in each case. This kind of indemnification rule varies by contracts, and it is almost impossible to generalize this. Therefore, this paper propose Rule IV as a simple example of the indemnification rule. In other words, even if this islanding event determined by one party cause damage to/increase the operating cost of the counter party, each party does not provide any compensation for the other's loss. Instead, Rule IV assume that both parties take all the loss from the islanding by themselves in any case.

2.4 Microgrid Islanding Rule B

As mentioned in Section 2.3, many researches represent that the island operation of a microgrid is an action that is intentionally taken by the MGO to protect its reliable operation when a large disturbance occurs outside its grid. This kind of intentional islanding, which is decentrally taken by each individual MGO, is a distinct characteristic of microgrid operation unlike the traditional system operation. On the other hand, Microgrid Islanding Rule A in Section 2.3 proposes a different viewpoint on the microgrid island operation, which can be treated as a load shedding taken by system operator (SO) to maintain the system frequency. That is, it presents that microgrids are also a kind of generic distribution network and they could be disconnected from the main grid by SO if the system reliability is impeded by them. However, Rule A has a limit that microgrid islanding is treated only as a load-shedding taken by SO, and even this is confined to a simple rule: “A breach of contract unconditionally triggers islanding event.” This constrained assumption is impractical to apply the method to the real system. Therefore, this section revise the Microgrid Islanding Rule A to realistically consider the island operation of the microgrid in the operation and planning level. In order to this, generalized triggering condition of microgrid islanding is applied to the new rule as below:

Rule B-I: SO can disconnect the microgrid who violates its reserve band contract if it is needed for the system frequency regulation.

Rule B-II: MGO, who violates its reserve band contract but do not get the disconnection, has to pay a penalty for the violation.

Rule B-III: When a disturbance occurs in the grid, SO and any MGOs can take island operation of the microgrids. This islanding is a protective action for their reliable operation, and can arise anytime regardless of reserve band violation.

Rule B-IV: If islanding occurs during a given step of a stage, it lasts for the duration of the remaining steps of that stage, as well as the following next stage, after which the microgrid tries to reconnect to the main grid.

Rule B-V: Reconnection trial of islanded microgrid can fail. In case of failure, the MGO can try reconnection again at the next stage.

Rule B-VI: Transaction prohibition during the determined period of time stated in Rule IV is the only penalty for the islanding, and there are no additional penalties to SO and MGOs, such as imposition of a fine.

In Rule IV, the step and the stage represent time units for the occurrence of islanding and the contract in the PXFC market, respectively; in the simulation part of this paper we assume that each stage consists of six steps, although other systems may use a different number.

According to Rule I, islanding event maybe or maybe not occur even if a MGO violate its reserve band contract. In other words, MGO's breach of the contract is a soft condition in the revised rule, whereas it was a hard condition in the Rule A. This is much more realistic considering that the influence of the power flow uncertainty between the main grid and the microgrid on the system frequency and voltage, can change by system operating point and system uncertainty. For example, if SO impose island operation on a microgrid when the system is stable, it could be an unintentional disturbance that is caused by SO and can affect system stability. Therefore, SO has to consider not only the contract observance of a microgrid but also total system condition to operate the system stably and reliably. However, if Rule I exists alone, there could be some optimistic or selfish MGO who purchases smaller reserve band from the market than the imbalance that it actually generates. To solve this problem, Rule II, which imposes a penalty on the contract violator, is proposed as a compensator of Rule I. Therefore, MGO has to purchase its reserve band capacity from the market, considering the risk of both island operation and penalty payment under the revised market rule. Rule III represents another microgrid islanding caused by disturbance in the system. This kind of islanding can occur irrelevant to the contract violation in order to protect reliable operation of each MGO or SO. Many accidents, such as over-flow by line fault in the network or shortage of system reserve by sudden demand increase, can trigger this. Therefore, Rule I and III enable this paper to include the islanding event that is triggered by various causes in other researches [16]-[18]. Rule IV is equal the Rule III in Section 2.3 and specify the minimal duration of islanding, which can be determined by market regulation and physical constraint.

Newly added Rule V represents the reconnection event after islanding. Generally synchronization should be done before two different system connects, whether they are single generators or large power grids. The same applies to microgrid. Many researches have been proposed about the synchronization scheme of a microgrid in the islanded mode [31]-[33]. Enough energy and time are needed for the synchronizing process, and the connection could end in failure without well-done synchronization [31]. Furthermore, since there could be many unpredictable and changing distributed energy resources in the microgrid, it would be very challenging for MGO to synchronize its frequency and voltage to the main grid. Therefore, the analysis of microgrid synchronization and reconnection, which can affect the duration of island operation, needs to be carried out for evaluating the risk of island operation. For this, Rule A in Section 2.3 just defined a minimum duration of island operation. However, this deterministic method has some limit to consider many changing factors in the microgrid that can affect the success of reconnection. With new Rule V, the increase of islanded operating cost from the failure of reconnection can be included in the calculation.

Chapter 3. Optimal Operation Strategy by Microgrid Operator for Microgrid Islanding Rule A

3.1 Objective Function and Problem Formulation for Rule A

The problem of microgrids in the PXFC market is to find an optimal band $\mathbf{BD}^*$ that minimizes the daily operating costs of the microgrid. This can be formulated as an optimization problem with respect to $\mathbf{BD}$; i.e.,

$$\min_{\mathbf{BD}} C_{TOT} \tag{3-1}$$

where $\mathbf{BD} = [BD_1, \cdots, BD_{N_{stage}}]^{\mathbf{T}}$. The objective function C_{TOT} can be formulated as:

$$\begin{aligned} C_{TOT} &= (\mathbf{1} - \mathbf{k}(\mathbf{BD}))^{\mathbf{T}} \cdot \mathbf{CG}(\mathbf{BD}) + \mathbf{k}^{\mathbf{T}}(\mathbf{BD}) \cdot \mathbf{CI} \\ &= \sum_{i=1}^{N_{stage}} \left[\left\{ 1 - k_{\mathrm{i}}(\mathbf{BD}) \right\} \cdot CG_{\mathrm{i}}(BD_i) + k_{\mathrm{i}}(\mathbf{BD}) \cdot CI_{\mathrm{i}} \right] \end{aligned} \tag{3-2}$$

where islanding is represented by a new variable $\mathbf{k} = [k_1, \cdots, k_{N_{stage}}]^T$, which represents microgrid islanding probability (MIP), and $\mathbf{CG} = [CG_1, \cdots, CG_{N_{stage}}]^{\mathbf{T}}$ and $\mathbf{CI} = [CI_1, \cdots, CI_{N_{stage}}]^{\mathbf{T}}$ are the operating costs in the grid-connected and islanded modes. The variable k_i indicates the probability of being in the islanded state during the *i*-th stage, which is determined as the ratio of the expected number of steps while in the islanded mode to the total number of steps in a stage, N_{step}. Therefore, (3-2) is similar to the representation of expected outage cost, which is the multiplication of loss of load expectation (LOLE) and value of lost load (VOLL), and it enables to evaluate the risk of islanding event in the operation level.

Equation (3-2) shows that the operating cost of the microgrid can be represented as a probabilistic linear combination of the operating cost in the grid-connected mode, $\mathbf{CG}$, and the operating cost in the islanded mode, $\mathbf{CI}$. Generally $\mathbf{CG}$ includes band purchase cost and energy supply cost, consisting of energy purchase cost as well as self-generation cost. And $\mathbf{CI}$ includes prepararion cost for reconnection and energy supply cost, consisting of self-generation cost as well as load-shedding cost. However, specific operating cost of a microgrid in each mode will be a case-by-case function according to the DERs that MGO owns. Therefore, next Section 3.2 will examine the cost functions postulated in this paper.

3.2 Defining the Cost Functions for Rule A

Prior to establishing the operation strategy, MGO has to forecast its demand and uncontrollable generation at first, and MGO can define its operating cost both in the grid-connected mode and the islanded mode with these forecasted value and market information. First, the postulated operating cost function in the grid-connected mode is as below.

$$CG_i = EG_i + RG_i\left(\mathrm{BD}_i\right) \tag{3-3}$$

where EG_i is the energy supply cost and RG_i is the reserve supply cost in the grid-connected mode during *i*-th stage. The energy supply cost terms EG_i in (3-3) is determined using a procedure similar to economic dispatch; i.e.,

$$EG_i = \min_{(x_i^{G,int},\ x_i^{ext})}\left[G_i(x_i^{G,int}) + M_i(x_i^{ext})\right] \tag{3-4}$$

where the sum of $x_i^{G,int}$ and $x_i^{I,int}$ should be equal to the forecasted demand of the microgrid. For the Microgrid Islanding Rule A, the reserve market cost term RG_i is equal to the band purchase cost i.e.,

$$RG_i = \lambda_{BD_i} \cdot BD_i \tag{3-5}$$

Similarly the islanded operating cost CI_i is comprised of energy supply and reconnection costs; i.e.,

$$CI_i = EI_i + RI_i \tag{3-6}$$

where EG_i is the energy supply cost and RG_i is the reconnection cost in the islanded mode during *i*-th stage. The energy supply cost terms EI_i in (3-6) is determined using a procedure similar to the above; i.e.,

$$EI_i = \min_{(x_i^{I,int},\ x_i^{LS})} \left[G_i(x_i^{I,int}) + LS_i(x_i^{LS}) \right] \tag{3-7}$$

where the sum of $x_i^{I,int}$ and x_i^{LS} should be equal to the forecasted demand of the microgrid. Assuming that load shedding does not occur in the grid-connected mode (i.e., there is sufficient generation capability in the main grid and the price of load shedding is much higher than this), the load shedding cost LS_i is not included in EG_i. The reconnection cost term RI_i represents all the cost that MGO has to pay during island operation except for the energy cost: control cost for stabilization and reconnection, wear cost for switching, etc.

3.3 Microgrid Islanding Model for Rule A

Islanding Rule A-I represents the triggering condition of microgrid islanding: An islanding event is triggered only by the breach of reserve band contract. Since many factors may lead to variations in the power flow between the main grid and a microgrid, including the forecast error and line fault, if the MGO determine the causes and develop a mathematical model for the variation, the probability of islanding may be represented based on such a model as a function of the frequency control band. In other words, if a variation model during the *j*-th step of the *i*-th stage is given, the relation between the probability of islanding p_{ij} and the frequency control band BD_i can be represented as

$$p_{ij} = 1 - q_{ij} = \int_{-\infty}^{-BD_i} f_{\Delta_{ij}} \cdot d\Delta_{ij} + \int_{BD_i}^{\infty} f_{\Delta_{ij}} \cdot d\Delta_{ij} \tag{3-8}$$

where Δ_{ij} is the uncertainty deviation of the microgrid during the *j*-th step of the *i*-th stage and $f_{\Delta_{ij}}$ is the probability density function of Δ_{ij}. The first term on the right side of (3-8) represents the probability when the value of variation is below $-BD_i$, and the second term represents the probability when the value of variation is greater than BD_i.

Since the probability of triggering the microgrid island operation is defined as above, an islanding event can be regarded as a binomial or Bernoulli event of having the event probability of p_{ij}. A Bernoulli trial is a random experiment with two outcomes: “success” and “failure”, in which the probability of success or failure always has the same value. Here we establish a binomial probabilistic model for microgrid islanding, which consists of success/failure experiments for microgrid islanding that are analogous to the Bernoulli trial with a variable probability. The microgrid islanding rules given in Section II can be interpreted based on this model as follows, which is illustrated in Figure 3.1.

- The proposed binomial model consists of a sequence of $N_{stage} \times N_{step}$ success/failure experiments, where success corresponds to islanding and the result of an experiment is dependent on previous experiments.

- During the *j*-th step of the *i*-th stage, the state X_{ij} prior to the experiment is 0.

- The success probability (probability of islanding) during the *j*-th step of the *i*-th stage is p_{ij}.

- If islanding occurs during the *j*-th step of the *i*-th stage, then the state X_{ij} becomes 1.

- This state transition is maintained until the N_{step}-th step of the (*i*+1)-th stage. This means that the success/failure of an experiment affects the results of subsequent experiments.

- During the *j*-th step in the *i*-th stage, the state 0 incurs a cost CG_i / N_{step} and a state of 1 incurs a cost CI_i / N_{step}.

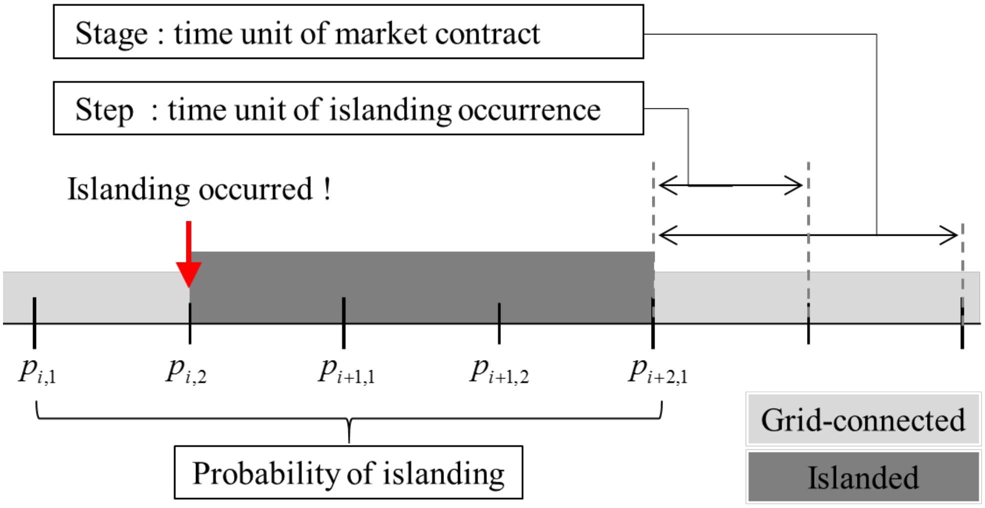

Figure 3.1 Representation of the microgrid islanding as a set of Bernoulli experiments

3.4 Formulating Microgrid Islanding Probabaility for Rule A

The MIP is calculated using the values of the probability of islanding. It should be noted that MIP and the probability of islanding are different. MIP is the ratio between the expected number of steps in which the islanded state is maintained in a stage and the total number of steps in that stage, whereas the probability of islanding is the probability that islanding will occur during any step in the stage. For example, suppose there is one stage consisting of two steps with the same probability of islanding of $p_{ij} = 0.1$, MIP k_1 can be determined based on two cases: with two islanded steps, where islanding occurs during the first step and continues into the second step, and with one islanded step, where islanding occurs during the second step. In this case MIP is given by

$$k_1 = \frac{(0.1 \times 2\,\text{steps}) + (0.9 \times 0.1 \times 1\,\text{step})}{2\,\text{steps}} = 0.145\,. \tag{3-9}$$

The general expression of MIP over multiple stages in practical situation can be derived by examining the form of the expected operating cost of the microgrid in a day. To calculate the expected incurred cost during the *i*-th stage, two cases are considered at the start of the *i*-th stage: $X_{i,0+} = 0$ (grid-connected) and $X_{i,0+} = 1$ (islanded) where $X_{i,0+}$ is the islanding state immediately prior to the binomial experiment during the first step of the *i*-th stage.

In the first case ($X_{i,0+} = 0$), the state may persist until the end of the *i*-th stage (i.e., with no “success” experiments). Then the expected cost C_i^{0-0} can be calculated as

$$C_i^{0-0} = CG_i \times P_i^{0-0} \tag{3-10}$$

where P_i^{0-0} is the probability of no “success” experiments in any of the steps of the *i*-th stage, which is expressed as

$$P_i^{0-0} = \prod_{j=1}^{N_{step}} \left(1 - p_{i,j}\right) = \prod_{j=1}^{N_{step}} \left(q_{i,j}\right). \tag{3-11}$$

The superscript 0-0 in C_i^{0-0} and P_i^{0-0} indicates that the stage begins and ends in a grid-connected state. However, it is also possible that islanding occurs during a step of the *i*-th stage. Suppose that islanding occurs during the *j*-th step of the *i*-th stage; the incurred cost C_{ij}^{0-1} is given by

$$C_{i,j}^{0-1} = \left(j-1\right) \times \frac{CG_i}{N_{step}} + \left(N_{step} - j + 1\right) \times \frac{CI_i}{N_{step}}. \tag{3-12}$$

Because islanding may occur during any step of the *i*-th stage, the expected cost C_i^{0-1} for the *i*-th stage can be represented as

$$C_i^{0-1} = \sum_{j=1}^{N_{step}} \left(C_{i,j}^{0-1} \times P_{i,j}^{0-1}\right) \tag{3-13}$$

where P_{ij}^{0-1} is the probability that islanding occurs during the *j*-th step of the *i*-th stage and is expressed as

$$P_{i,j}^{0-1} = \left\{ \prod_{m=1}^{j-1} \left(q_{i,\mathrm{m}} \right) \right\} \times p_{i,\mathrm{j}} \tag{3-14}$$

When $j = 1$ in (3-14), the value in the curly bracket is defined as 1, that is, $\prod_{m=1}^{0} \left(q_{i,\mathrm{m}} \right) = 1$. Then, the expected value of the incurred costs for the *i*-th stage in the case of $X_{i,0+} = 0$ becomes the sum of C_i^{0-0} and C_i^{0-1}.

The second case of $X_{i,0+} = 1$ in the model considers a situation whereby islanding occurred during the (*i*-1)-th stage, and the state transition persists for the *i*-th stage. The expected cost C_i^{1-1} is easily determined as

$$C_i^{1-1} = CI_i \times P_i^{1-1} = CI_i \times 1 \tag{3-15}$$

where P_i^{1-1} is the probability that all the steps in the *i*-th stage are in the state 1 when $X_{i,0+} = 1$, and it is clear that $P_i^{1-1} = 1$ from the Rule A-III.

The expected value of the overall cost C_{TOT} for all stages is given by

$$C_{TOT} = \sum_{i=1}^{N_{stage}} \left\{ \Pr(X_{i,0+} = 0) \times \left(C_i^{0-0} + C_i^{0-1} \right) + \Pr(X_{i,0+} = 1) \times C_i^{1-1} \right\}, \tag{3-16}$$

where $\Pr(X_{i,0+} = 0)$ and $\Pr(X_{i,0+} = 1)$ are the probabilities that $X_{i,0+} = 0$ and

$X_{i,0+} = 1$ at the start of the i-th stage, respectively, and $\Pr(X_{i,0+} = 1) = 1 - \Pr(X_{i,0+} = 0)$. They have some relationship according to the Microgrid Islanding Rule A, which may be represented by a recurrence equation, as follows:

$$\Pr(X_{i,0+} = 0) = \left\{ \Pr(X_{i-1,0+} = 0) \times \prod_{j=1}^{N_{step}} \left(q_{i-1,j} \right) \right\} + \left\{ \Pr(X_{i-1,0+} = 1) \times 1 \right\} \quad (3\text{-}17)$$

The first term on the right-hand side of (3-17) represents the situation whereby $X_{i-1,0+} = 0$ is maintained until the beginning of the i-th stage. In this case, there were no "success" experiments during the (i-1)-th stage. The second term corresponds to $X_{i-1,0+} = 1$, which means that there was a "success" experiment during the (i-2)-th stage, and so the i-th stage can always begin with the 0 state, according to the penalty rules. To complete the recurrence formula, $\Pr(X_{1,0+} = 0) = P_0$ is assumed as a starting condition in the first stage.

Consequently, MIP can be derived by comparing C_{TOT} in (3-2) with C_{TOT} in (3-16), after substituting (3-10), (3-13), and (3-15) into C_i^{0-0}, C_i^{0-1}, and C_i^{1-1}, respectively. After some rearrangement, MIP k_i is given by

$$k_i = \Pr(X_{\mathrm{i},0+} = 0) \times \sum_{j=1}^{N_{step}} \left\{ \left(\frac{N_{step} - j + 1}{N_{step}} \right) \cdot \left(p_{i,\mathrm{j}} \prod_{m=1}^{j-1} q_{i,\mathrm{m}} \right) \right\} + \Pr(X_{\mathrm{i},0+} = 1) \times 1 \quad (3\text{-}18)$$

where $\Pr(X_{i,0+} = 0)$ and $\Pr(X_{i,0+} = 1)$ are calculated using the recurrence relation in (3-17). It follows that MIP k_i is not only a function of BD_i but it is implicitly affected by all the previous decisions for band capacity.

Chapter 4. Numerical Simulation I for Microgrid Islanding Rule A

4.1 Simulation Settings

A day is comprised of 24 stages and each stage has six steps in the simulations. Regarding the starting condition in the first stage, $P_0 = 1$ is assumed for simplicity. Two microgrids with different generation capability are considered, denoted as MG-A and MG-B, and are as follows

MG-A: The generation capability of the microgrid is sometimes larger than demand in the microgrid.

MG-B: The generation capability of the microgrid is always smaller than demand in the microgrid.

The specific daily cost functions in (3-3)–(3-7) for MG-A are formulated by taking the values given in [12] and [24], as follows:

$$G_i(x_i^{int}) = 48.425 \cdot x_i^{int} \quad \text{for } 10 \le x_i^{int} \le 40 \tag{4-1}$$

$$M_i(x_i^{ext}) = \lambda_i^E \cdot x_i^{ext} \quad \text{for } 10 \le x_i^{ext} \le 50 \tag{4-2}$$

$$LS_i(x_i^{LS}) = 3000 \cdot x_i^{LS} \quad \text{for } 0 \le x_i^{LS} \le x_i^{int} + x_i^{ext} \tag{4-3}$$

$$RG_i(BD_i) = \lambda_i^{BD} \cdot BD_i \tag{4-4}$$

$$RI_i = 30 \tag{4-5}$$

where x_i^{int} represents either $x_i^{G,int}$ or $x_i^{G,ext}$ depending on the corresponding operating mode, and λ_i^E and λ_i^{BD} represent the hourly prices of the energy market and the band market, respectively. For MG-B, only the maximum generation capability of 40 MW in (4-1) was replaced with 30 MW, and other coefficients in (4-1)–(4-5) were as MG-A. In particular, for (4-3) and (4-5), the results of the value of lost load (VOLL) of various sectors in [24] were used to determine the coefficient in (4-3), and 1% of this value was assumed as the reconnection cost in (4-5). Each microgrid is assumed as a price taker in the energy and band markets, and day-ahead locational marginal prices from PJM on July 15, 2014 [25] were used for λ_i^E and λ_i^{BD}. In the PXFC market, trades are made simultaneously within both the energy and the band markets. Therefore, the price difference between two markets may lead to a complex situation requiring a strategic decision of the participants [26]. For this reason, the same values are employed for λ_i^E and λ_i^{BD} here. The forecast demand for the microgrids was determined based on the day-ahead market demand from PJM on the same day, and scaled with a maximum of 50 MW. The Gaussian distribution with the mean of zero and the variance of σ_{ij}^2 was used as a variation model in (9). The standard deviation σ_{ij} was constant in each stage, and was randomly determined in the range 5–20% of the forecast demand. The probability of islanding p_{ij} can be calculated from the corresponding standard deviation, as described by (3-8). Specific values of the market prices, forecast demand, and the associated standard deviation are given in Table 4.1.

To investigate the effectiveness of the proposed approach, the following three methods, which have similar reserve supply cost RG_i, were studied using two microgrids.

Method I: Reserve band capacity determined using the proposed method

($BD_i = BD_i^*$ from (3-1)).

Method II: A constant reserve band capacity ($BD_i = 20\,\mathrm{MW}$).

Method III: The ratio of the reserve band capacity to the standard deviation is

constant ($BD_i = 4 \times \sigma_{i,j}$).

These six cases are denoted so that, for example, Case I-A corresponds to Method I and MG-A. The simulations are performed with MATLAB R2013b, and the optimization problems are solved by the pattern search algorithm [27].

Table 4.1 Simulation Parameters for Microgrid Islanding Rule A

Stage	1	2	3	4	5	6
Forecasted demand [MW]	36.78	34.61	33.24	32.42	32.52	33.87
Standard deviation [MW]	5.52	6.43	6.03	1.84	5.79	5.3
Market price [$/MWh]	29.74	27.54	26.32	25.64	25.65	27.15
Stage	7	8	9	10	11	12
Forecasted demand [MW]	36.76	39.88	42.02	44.34	46.4	48.26
Standard deviation [MW]	4.57	5.01	6.32	8.45	3.24	3.79
Market price [$/MWh]	29.44	30.79	34.97	38.52	43.33	46.3
Stage	13	14	15	16	17	18
Forecasted demand [MW]	48.95	49.8	49.95	50	49.72	48.54
Standard deviation [MW]	6.28	2.52	9.36	3.62	4.01	7.68
Market price [$/MWh]	48	51.4	52.83	53.91	50.83	48.8
Stage	19	20	21	22	23	24
Forecasted demand [MW]	47.51	46.13	45.57	44.56	41.58	37.76
Standard deviation [MW]	4.38	3.4	3.73	4.79	3.61	1.9
Market price [$/MWh]	43.09	39.26	38.65	37.43	32.21	30.56

4.2 Simulation Results

The simulated total operating cost is listed in Table 4.2 and the corresponding band capacity for each stage is listed in Table 4.3. With MG-A, the operating costs with our method were reduced by 23.37% compared with Method II and 4.51% compared with Method III. With MG-B, the operating costs with our method were reduced by 35.75% compared with Method II and 0.71% compared with Method III.

With Method II, the variation of the demand and the economic conditions, including the market price and generation cost, are not considered in determining the band capacity. Thus, the microgrid may prepare an excessive reserve band capacity, which may result in an excessive increase in the grid-connected operating cost CG_i; or the microgrid may prepare an insufficient reserve band capacity, which increases the risk of islanding and makes the MGO suffered from excessive islanded operating costs CI_i due to an exorbitant load shedding cost LS_i. Therefore, our method outperforms Method II in terms of the operating cost. Method III exhibited significantly better performance than Method II because it considers the demand variation. In particular, with MG-B, our method resulted in a reduction in costs of only 0.71% compared with Method III. This is because MG-B has a relatively small generation capability, so that MG-B should lead to load shedding more frequently and largely in the islanded mode. Therefore, as shown in Figure 4.1, the operating cost in the islanded mode was significantly larger for MG-B than for MG-A. In this case, preventing islanding by preparing the reserve band capacity in proportion to the variation in demand may be a solution to minimize the operating costs. In other words, Method III is a simple alternative to

Table 4.2 Expected value of total operating cost of MG-A and MG-B according to the determination of reserve band capacity for Microgrid Islanding Rule A

	MG-A	MG-B
Method I	$ 51,384	$ 54,633
Method II	$ 67,051	$85,028
Method III	$ 53,810	$ 55,021

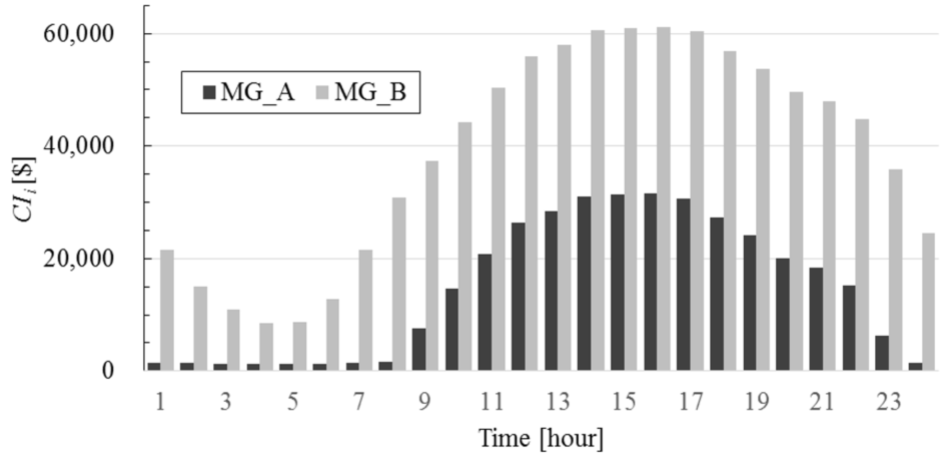

Figure 4.1 Operating cost of MG-A and MG-B in the islande mode (CI_i)

Table 4.3 Optimal band capacity and MIP values of the six cases for Microgrid Islanding Rule A

Stage		1	2	3	4	5	6	7	8	9	10	11	12
Band capacity [MW]	Case I-A	10.49	12.6	14.35	5.14	12.63	11.79	6.97	16.03	21.49	29.07	12.2	14.14
	Case I-B	20.07	22.56	20.88	6.93	20.45	19.52	17.44	19.26	23.98	31.54	12.91	14.92
	Case II-A/B	20	20	20	20	20	20	20	20	20	20	20	20
	Case III-A/B	22.1	25.71	24.14	7.35	23.17	21.19	18.28	20.05	25.29	33.8	12.98	15.15
MIP	Case I-A	0.1835	0.4125	0.2334	0.0977	0.1225	0.2319	0.441	0.4917	0.0066	0.0061	0.0041	0.0017
	Case I-B	0.001	0.0032	0.0046	0.0038	0.0024	0.0033	0.0018	0.0012	0.0012	0.0016	0.0014	0.0007
	Case II-A/B	0.001	0.0082	0.0143	0.0055	0.002	0.0039	0.001	0.0003	0.0058	0.0697	0.1019	0.0001
	Case III-A/B	0.0002	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006

Table 4.3 Optimal band capacity and MIP values of the six cases for Microgrid Islanding Rule A (continue)

Stage		13	14	15	16	17	18	19	20	21	22	23	24
Band capacity [MW]	Case I-A	22.69	9.69	32.61	13.56	14.83	26.86	15.96	12.58	13.57	16.29	11.2	4.4
	Case I-B	23.93	10.15	34.47	14.23	15.65	28.65	17.05	13.48	14.68	18.37	13.95	7.11
	Case II-A/B	20	20	20	20	20	20	20	20	20	20	20	20
	Case III-A/B	25.12	10.08	37.43	14.5	16.03	30.73	17.52	13.59	14.93	19.14	14.42	7.59
MIP	Case I-A	0.0022	0.0022	0.0024	0.0036	0.0018	0.0029	0.0037	0.0023	0.0023	0.004	0.0106	0.0797
	Case I-B	0.001	0.001	0.0011	0.0017	0.0008	0.0012	0.0015	0.0008	0.0007	0.0009	0.0011	0.0013
	Case II-A/B	0.0051	0.0087	0.108	0.1801	0.0001	0.0319	0.0541	0.0001	0.0001	0.0002	0.0002	0.0001
	Case III-A/B	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006

our method for a microgrid without sufficient generation capability, even though it becomes difficult to select a suitable scaling factor to the variation of the demand, which was set to 4 here. However, if an excessively high band price increases CG_i so that it is comparable to CI_i, it would be better to accept the risk of islanding by decreasing the band capacity. Because these economic conditions are not considered with Method III, such a flexible determination of the band capacity is not possible, and it is clear that Method III will perform significantly less well than our method.

The MIPs for each stage are listed in Table 4.3. It should be noted that the MIPs for Cases II-A and II-B are listed together in Table 4.3, as they were equal because they had the same band capacity. The same description is applied to Cases III-A and III-B. Considering that CI_i is typically larger than CG_i, a microgrid in the PXFC market should decrease the total operating cost C_{TOT} in (3-2) by increasing the band capacity BD_i, and accordingly decreasing MIP k_i. The increase in BD_i, however, affects not only k_i but also the grid-connected operating cost CG_i in (3-3). In other words, the increase in BD_i makes k_i smaller, but also results in an increase in the other term related to CG_i. It follows that C_{TOT} has a trade-off between k_i and CG_i with respect to the band capacity. Moreover, it can be seen from Figure 4.1 that the values of CI_i are very small, especially in the stages 1–8 and 24, where MG-A could operate without load shedding even when islanded, in contrast to MG-B. Because of this, MIP with Case I-A was on average 133-fold larger than with Case I-B in those periods. This analysis suggests that an MGO with a small CI_i should prepare a smaller reserve band capacity to reduce the total operating costs, even though the risk of islanding will increase.

As was described in Section IV, MIP depends on not only the current decisions for the band capacity, but also the previous decisions, in contrast to the probability of islanding. To demonstrate this property of the MIP, in Figure 4.2 we plot MIP k_i and the probability of islanding p_{ij} for Case II-A/B; p_{ij} was largest during the 15th stage, yet k_i was largest during the 16th stage. Since the occurrence of islanding in a stage affects the subsequent stage because of the penalty rules, the large value of $p_{15,j}$ means that all the steps during the 16th are more likely to be islanded, which results in the large k_{16}. For the same reason, there was a high probability that the 17th stage will begin in the grid-connected mode. Thus k_{17} was smaller than k_{14} by a factor of almost 100, although the reserve band capacities in both stages were identical and $\sigma_{17,j}$ differed from $\sigma_{14,j}$ by a factor of 1.6. Because of this complex time dependence of the MIP, determining the optimal band capacity requires a numerical approach.

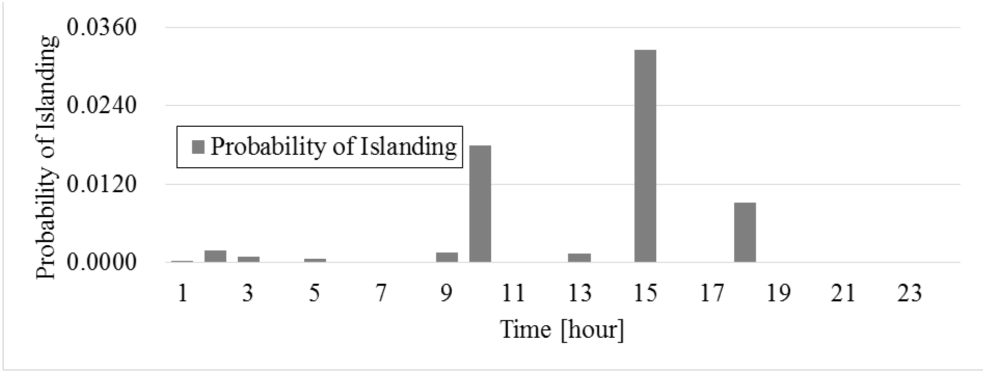

Figure 4.2 (a) Probability of islanding for Case II-A/B

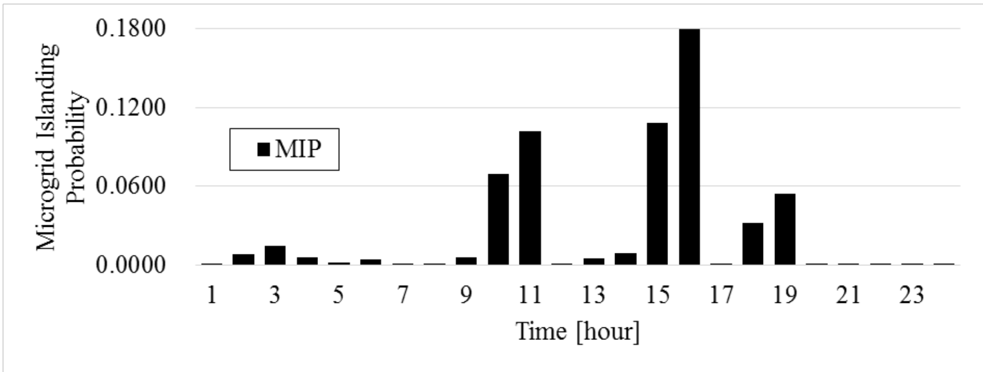

Figure 4.2 (b) The MIP values for Case II-A/B

Chapter 5. Optimal Operation Strategy by Microgrid Operator for Microgrid Islanding Rule B

5.1 Objective Function and Problem Formulation for Rule B

The problem of MGO in the PXFC market with Microgrid Islanding Rule B is equal to the problem defined in Section 3.1. In other words, the problem is to find an optimal band $\mathbf{BD}^*$ that minimizes the daily operating costs of the microgrid. Therefore the optimization problem is formulated as follows,

$$\min_{\mathbf{BD}} C_{TOT} \tag{5-1}$$

where $\mathbf{BD} = [BD_1, \cdots, BD_{N_{stage}}]^{\mathbf{T}}$. Likewise the objective function C_{TOT} can be formulated as:

$$\begin{aligned} C_{TOT} &= (\mathbf{1} - \mathbf{k}(\mathbf{BD}))^{\mathbf{T}} \cdot \mathbf{CG}(\mathbf{BD}) + \mathbf{k}^{\mathbf{T}}(\mathbf{BD}) \cdot \mathbf{CI} \\ &= \sum_{i=1}^{N_{stage}} \left[\left\{ 1 - k_{\mathrm{i}}(\mathbf{BD}) \right\} \cdot CG_{\mathrm{i}}(BD_i) + k_{\mathrm{i}}(\mathbf{BD}) \cdot CI_{\mathrm{i}} \right] \end{aligned} \tag{5-2}$$

Although Equation (3-1) and (5-1) seems to be the same, two optimization problems are different problems based on different islanding rule. Therefore the operating costs both in the grid-connected mode and islanded mode as well as the MIP index will have different form. Next Section 5.2, 5.3 and 5.4 will examine the differences in cost functions, islanding model, and MIP formulation based on the

Rule B.

5.2 Defining the Cost Functions for Rule B

Prior to establishing the operation strategy, MGO has to forecast its demand and uncontrollable generation at first. With these forecasted value and market information, MGO can define its operating cost in the grid-connected mode as below.

$$CG_i = EG_i + RG_i\left(\mathrm{BD}_i\right) \tag{5-3}$$

The reserve market cost term RG_i consists of band purchase cost and imbalance penalty cost of Rule II;i.e.,

$$RG_i = \lambda_{BD_i} \cdot BD_i + \sum_j PG_{ij} \tag{5-4}$$

The imbalance penalty cost PG_{ij} is determined from the prearranged mutual agreement among market participants. This paper refers to [34], [35] and defines the penalty cost function as the multiplication of the penalty price and band violation capacity as below.

$$PG_{ij} = \begin{cases} \lambda_i^{PG} \cdot \left|\Delta_{i,j} - \mathrm{BD}_i\right| & \text{if } \left|\Delta_{i,j}\right| > BD_i \\ 0 & \text{otherwise} \end{cases} \tag{5-5}$$

Similarly, considering the maximum generation capacity and value of lost load in the microgrid, MGO can define its operating cost in the islanded mode as below.

$$CI_i = EI_i + RI_i \tag{5-6}$$

The reconnection cost RI_i represents all the cost that MGO has to pay during island operation except for the energy cost: control cost for stabilization and reconnection, wear cost for switching, etc. The respective energy supply cost terms EG_i in (5-3) and EI_i in (5-6) are determined using a procedure similar to economic dispatch; i.e.,

$$EG_i = \min_{(x_i^{G,int},\ x_i^{ext})} \left[G_i(x_i^{G,int}) + M_i(x_i^{ext}) \right] \tag{5-7}$$

$$EI_i = \min_{(x_i^{I,int},\ x_i^{LS})} \left[G_i(x_i^{I,int}) + LS_i(x_i^{LS}) \right] \tag{5-8}$$

where the sum of $x_i^{G,int}$ and $x_i^{I,int}$ as well as the sum of $x_i^{I,int}$ and x_i^{LS} should be equal to the forecasted demand of the microgrid. Assuming that load shedding does not occur in the grid-connected mode (i.e., there is sufficient generation capability in the main grid and the price of load shedding is much higher than this), the load shedding cost LS_i is not included in EG_i.

5.3 Microgrid Islanding Model for Rule B

Islanding Rule I and III in Section III generalize the triggering condition of microgrid island operation. Since this generalized island operation can be affected by not only the reserve band contract but also the system condition, the triggering condition (3-8) in Section 3.3 cannot be applied in this case. To resolve this problem, a conditional probability function, g_{ij}, which represents the islanding occurring probability according to Δ_{ij}, is newly defined in this Section. MGO can formulate the triggering condition using this probability function as below.

$$p_{i,j} = \int_{-\infty}^{\infty} \left\{ g_{ij}\left(\Delta_{i,j}, BD_i\right) \cdot f_{\Delta_{i,j}}\left(\Delta_{i,j}\right) \right\} d\Delta_{i,j} \tag{5-9}$$

$$g_{ij} = \Pr\left(\mathrm{A} \mid \Delta_{ij}\right) \tag{5-10}$$

where A is the event set of islanding occurring. g_{ij} is a function of Δ_{ij} and BD_i, which are the basic variables of reserve operation in PXFC market environment, and it should reflect the system condition that can affect microgrid island operation. Although g_{ij} can be a various kind of function by the grid condition and the market contract of MGO, generally g_{ij} can have any value between 0 and 1 and goes to the value of 1 as Δ_{ij} increases. This is because SO's burden on frequency regulation increases as the imbalance generated by MGO increases. Below sigmoid type function can be an example of the function g_{ij}.

$$g_{ij} = C + (1 - C) \cdot \left[1 + e^{-a \cdot (|\Delta_{ij}| - b \cdot \mathrm{BD}_i)} \right]^{-1} \tag{5-11}$$

The solid line in Figure 5.1 represents this conditional probability function of islanding from (5-11). This shows that islanding event occurs stochastically if MGO violates its reserve band contract, and there can be an islanding event even if MGO observes the market contract. Comparing two triggering conditions of islanding in (3-8) and (5-9), the shape of the conditional probability function from (3-8) can be get as the dashed line in Figure 5.1. This quantum-well shaped probability function shows that islanding event in Section 3.3 unconditionally occurs when the uncertainty of microgrid exceeds the purchased band capacity. In other words, triggering condition of islanding in Section 3.3 is a hard condition of band reserve contract.

Microgrid islanding model (5-9) with the conditional probability function clarifies the triggering condition of islanding from Rule I and III, and enables to do quantitative analysis like MIP calculation. As accurate calculation of generator forced outage rate is a prerequisite for LOLE calculation and efficient power system planning, the proper modeling of g_{ij} is essential for evaluating the risk of island operation and optimal microgrid operation. Therefore, the microgrid islanding model g_{ij} is as important as the microgrid uncertainty model. However, MGO has to completely recognize not only the inner microgrid but also the outer main grid for the accurate islanding model. This situation seems to be impractical considering the traditional transmission/distribution system operation scheme. Therefore, in the decentralized environment where total system consists of multi-microgrids, it is needed to reestablish clear-cut lines of MGO's authority and responsibility such as accessible information level. However, the main subject of this paper is to establish the optimal operation strategy of a microgrid considering the stochastic island operation. Therefore, this paper assumes that the islanding model g_{ij} is given with the uncertainty model $f_{\Delta_{ij}}$.

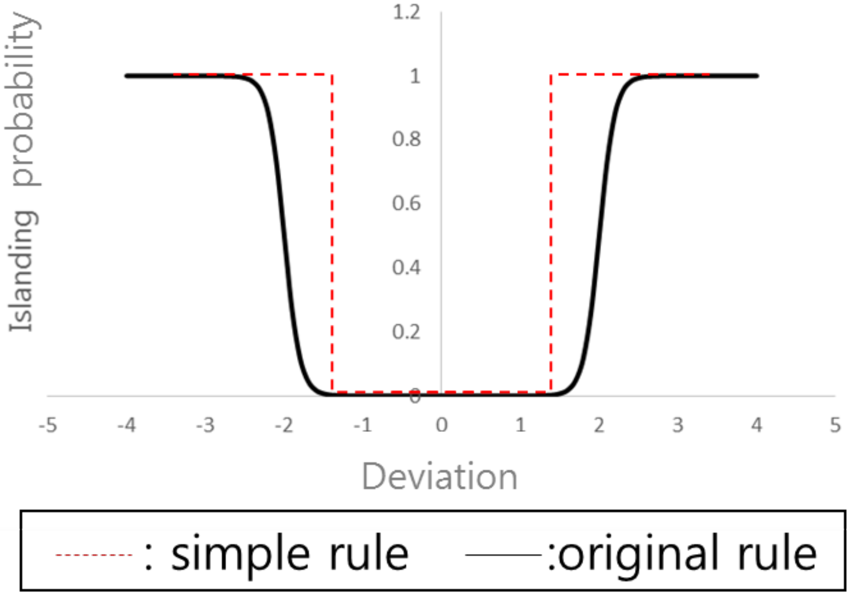

Figure 5.1 Two examples of microgrid islanding probability function

5.4 Formulating Microgrid Islanding Probabaility for Rule B

Like as Section 3.4, the expression of k_i can be derived by examining the form of the expected incurred cost during the *i*-th stage. To get this form, two cases are considered at the start of the *i*-th stage: $X_{i,0+} = 0$ (grid-connected) and $X_{i,0+} = 1$ (islanded).

In the first case ($X_{i,0+} = 0$), (i) the state may persist until the end of the *i*-th stage (i.e., with no islanding event) or (ii) the state may transfer during the stage (i.e., with islanding event). The expected cost of case (i) can be calculated as

$$C_i^{0-0} = \int_{\overline{\Delta}_i} CG_i(BD_i, \overline{\Delta}_i) \cdot \prod_{j=1}^{N_{stp}} \left\{1 - g_{ij}(BD_i, \Delta_{ij})\right\} \cdot f_{\overline{\Delta}_i} \cdot d\overline{\Delta}_i \qquad (5\text{-}12)$$

where the superscript 0-0 in C_i^{0-0} indicates that the stage begins and ends in a grid-connected state. Multiplication term of conditional probabilities in the integration indicates that there is no triggered islanding event during the stage. For the case (ii), if islanding occurs during the *j*-th step of *i*-th stage, the expected cost can be calculated as

$$C_{ij}^{0-1} = \int_{\overline{\Delta}_{ij}} \left(CG_{ij} + CI_{ij}\right) \cdot \left\{ \prod_{m=1}^{j-1} \left(1 - g_{ij}\right) \cdot g_{ij} \right\} \cdot f_{\overline{\Delta}_{ij}} \cdot d\overline{\Delta}_{ij} \qquad (5\text{-}13)$$

The term, $CG_{ij} + CI_{ij}$, indicates the incurred cost during the stage and can be respectively represented as below.

$$CG_{ij} = \left(\frac{j-1}{N_{stp}} \right) \cdot \left(EG_i + \lambda_{BD_i} \cdot BD_i \right) + \sum_{k=1}^{j-1} PG_{ik} \tag{5-14}$$

$$CI_{ij} = \left(\frac{N_{stp} - j + 1}{N_{stp}} \right) \cdot \left(CI_i \right) \tag{5-15}$$

where CG_{ij} is the operating cost before the islanding event occurs, and CI_{ij} is the operating cost after islanding event occurs. As case (i), the pi product term represents the event triggering probability. Since islanding event may occur during any step of the *i*-th stage, total expected cost of case (ii) can be represented as the summation of (5-16).

$$C_i^{0-1} = \sum_{j=1}^{N_{stp}} C_{i,j}^{0-1} \tag{5-16}$$

For the second case ($X_{i,0+} = 1$), the calculation of expected cost has to reflect the situations whereby islanding triggered during any previous stage and this islanded state persists for the *i*-th stage. For this case, the islanded microgrid tries to resynchronize and reconnect to the main grid during *i*-th stage. However, this trial can be success or failure. The expected value of operating costs for two cases, success and failure, are considered as below.

$$C_i^{1-0} = CI_i \cdot \alpha_i \tag{5-17}$$

$$C_i^{1-1} = CI_i \cdot \left(1-\alpha_i\right) \tag{5-18}$$

where α_i in (5-17) and (5-18) indicates the success probability of reconnection trial of i-th stage. As mentioned in Section III, success probability of reconnection trial depends on the grid condition and synchronization capability of MGO. Considering that generally the synchronization error is in inverse proportion to the time that is used for synchronizing, α_i can be represented as below.

$$\alpha_i = J\left(i,\mathrm{s}\right) \tag{5-19}$$

In other words, success probability of the reconnection trial is the function of current stage index i and the stage index s when the persisted islanded state started. And it has a value close to 1 if the time $(s-i)$ which is used for synchronizing increases. Therefore, α_i would be different even if two same microgrids tried to reconnect to the main grid at the same time, if the time of being in the island operation was different.

Consequently, the expected value of the overall operating cost for all stages is given by

$$C_{TOT} = \sum_{i=1}^{N_{stg}} \left[\left\{ \Pr\left(X_{i,0+}=0\right) \cdot \left(C_i^{0-0} + C_i^{0-1}\right) \right\} + \left\{ \Pr\left(X_{i,0+}=1\right) \cdot \left(C_i^{1-0} + C_i^{1-1}\right) \right\} \right] \tag{5-20}$$

MIP formulation can be derived by comparing (5-20) to (5-2). After substituting (5-12), (5-16), (5-17) and (5-18) into each C_i^{X-X} and some arrangement, MIP k_i

is given by

$$k_i = \Pr(X_{i,0+} = 0) \times \sum_{j=1}^{N_{stp}} \left[\left(\frac{N_{stp} - j + 1}{N_{stp}} \right) \cdot P_{no\_event}^{i,j} \right] + \Pr(X_{i,0+} = 1) \times 1 \qquad (5\text{-}21)$$

where $P_{no\_event}^{i,j} = \int_{\bar{\Delta}_i} \prod_{m=1}^{j} \{1 - g_{i\mathrm{m}}\} \cdot f_{\bar{\Delta}_i} \cdot d\bar{\Delta}_i$. $\Pr\left(X_{i,0+} = 0\right)$ and $\Pr\left(X_{i,0+} = 1\right)$ in (5-20) and (5-21) are the probabilities that $X_{i,0+} = 0$ and $X_{i,0+} = 1$ at the start of the *i*-th stage, respectively, and $\Pr\left(X_{i,0+} = 0\right) = 1 - \Pr\left(X_{i,0+} = 1\right)$. They have the relationship according to the Rule III and IV, which may be represented by a recurrence equation, as follows:

$$\begin{aligned} \Pr\left(X_{i,0+} = 0\right) &= \left[\Pr\left(X_{i-1,0+} = 0\right) \cdot P_{no\_event}^{i-1,N_{stp}} \right] \\ &+ \sum_{k=1}^{N_\alpha} \left[\Pr\left(X_{i-(k+1),0+} = 0\right) \cdot P_{event}^{i-(k+1)} \cdot \left\{ \prod_{l=2}^{k} \left(1 - \alpha_{i-l}\right) \cdot \alpha_{i-1} \right\} \right] \end{aligned} \qquad (5\text{-}22)$$

where $P_{event}^{i-(k+1)} = \left\{ 1 - \int_{\bar{\Delta}_{i-(k+1)}} \prod_{j=1}^{N_{stp}} \left\{1 - g_{i-(k+1),j}\right\} \cdot f_{\bar{\Delta}_{i-(k+1)}} \cdot d\bar{\Delta}_{i-(k+1)} \right\}$.

The first term on the right-hand side of (5-22) represents the situation whereby there were no islanding event during the (*i*-1)-th stage like (5-12) and $X_{i-1,0+} = 0$ is maintained until the beginning on the *i*-th stage. The second term represents all the situation whereby islanded state, which had been transferred during a prior stage, was recovered during the (*i*-1)-th stage and can start the *i*-th stage with grid-connected state. In other words, the sigma summation in the second term indicates that a microgrid started with grid-connected state at the beginning of (i-k+1)-th stage ($X_{i-(k+1),0+}=0$). However, there was an islanding event during this stage ($P_{event}^{i-(k+1)}$). This microgrid recovers its grid-connection after k times reconnection trial ($\prod_{l=2}^{k}\left(1-\alpha_{i-l}\right)\cdot\alpha_{i-1}$). The last number of sigma summation, N_α, is also a part of the reconnection trial model, and it means that this MGO is assumed to be able to succeed in recovering its grid-connection within N_α times trial.

The MIP expression in (5-21) is different from the expression in Section 3.4. This is because islanding event in this paper is stochastically triggered with the conditional probability whereas islanding event in Section 3.4 is deterministically triggered. In other words, the islanding event in this paper have the success probability between 0 and 1, and the islanding event in Section 3.4 always have the success probability of 0 or 1. These two situations can be liken to the situations whereby a man tosses a coin in two different room: a vacuum room and a windy room. If he knows the force applied to the coin, he can calculate the result perfectly in the vacuum room. On the other hand, he will make a wrong answer in the windy room without the wind condition, such as wind speed and direction. Moreover, if this wind vary with time, the results will be different each time even if he apply the same force. In order to get the right answer in both room, the experimenter has to know the external condition, i.e. wind condition. Likewise, MGO in this paper considers the condition of its external grid, which can affect the island operation and was not considered by MGO of Rule A, to figure out its island operation perfectly.

Chapter 6. Numerical Simulation II for Microgrid Islanding Rule B

6.1 Simulation Settings

Like as Section 4.1, a day is comprised of 24 stages in the simulations, which consists of 4 steps, and two microgrids denoted as MG-A and MG-B are considered. The cost functions of each microgrid in (5-3)-(5-8) are formulated by taking the values given in Section 4.1, as follows:

$$G_i(x_i^{int}) = 48.425 \cdot x_i^{int} \quad \text{for } 10 \le x_i^{int} \le G_{\max} \tag{6-1}$$

$$M_i(x_i^{ext}) = \lambda_i^E \cdot x_i^{ext} \quad \text{for } 10 \le x_i^{ext} \le 50 \tag{6-2}$$

$$RG_i(BD_i) = \lambda_i^{BD} \cdot BD_i + \sum_j PG_{ij}\left(\lambda_i^{PG}\right) \tag{6-3}$$

$$LS_i(x_i^{LS}) = 3000 \cdot x_i^{LS} \quad \text{for } 0 \le x_i^{LS} \le x_i^{int} + x_i^{ext} \tag{6-4}$$

$$RI_i = 30 \tag{6-5}$$

where x_i^{int} represents either $x_i^{G,int}$ or $x_i^{I,int}$ depending on the corresponding operating mode. The maximum generation capability $G_{\max}$ for MG-A and MG-B are 40 MW and 30 MW respectively. λ_i^E and λ_i^{BD} are hourly prices of the energy and reserve band market. It is assumed that λ_i^E and λ_i^{BD} have the same value and both MGOs are price takers, in order to exclude complex market operation and focus the relation between MGO's reserve operation strategy and islanding risk. Day-ahead locational marginal prices from PJM on August 20, 2015

[25] were used for λ_i^E and λ_i^{BD}, and penalty price λ_i^{PG} in (6-3) were set 125% of them. The values of forecasted demand of MG-A and MG-B were determined based on the day-ahead market demand from PJM on the same day, and scaled with a maximum of 50 MW. Normal Gaussian distribution with the mean of zero and the variance of σ_{ij}^2 was used as the uncertainty model in (5-9). The standard deviation σ_{ij} was randomly determined in the range 5–20% of the forecast demand. For the microgrid islanding model, the sigmoid shaped function in (5-11) was used as the islanding probability function. The coefficients of it were determined to have the islanding probability of 50% when each MGO violates the band contract and has a deviation of 200% of the contract capacity as below.

$$g_{ij} = 0.001 + 0.999 \cdot \left[1 + e^{-10 \cdot \left(\left| \Delta_{ij} \right| - 2 \cdot \mathrm{BD}_i \right)} \right]^{-1} \tag{6-6}$$

Reconnection model was determined as finishing the reconnection trial within 3 stages as below.

$$N_\alpha = 3, \quad \alpha_i = \begin{cases} 0.6 & if \;\; i - s = 1 \\ 0.8 & if \;\; i - s = 2 \\ 1.0 & if \;\; i - s = 3 \end{cases} \tag{6-7}$$

To investigate the effectiveness of the proposed method, three reserve operation methods were studied for two microgrids and compared: Method I that prepares reserve capacity as 20% of demand in each stage, Method II that is proposed in Section 3, and Method III that is proposed in Section 5. These six cases are denoted so that, for example, Case I-A corresponds to Method I and MG-A. Specific values of all the market and grid conditions are given in Table 6.1.

Table 6.1 Simulation Parameters for Microgrid Islanding Rule B

Stage	1	2	3	4	5	6
Forecasted demand [MW]	36.78	34.61	33.24	32.42	32.52	33.87
Standard deviation [MW]	5.52	6.43	6.03	1.84	5.79	5.3
Market price [$/MWh]	29.74	27.54	26.32	25.64	25.65	27.15
Stage	7	8	9	10	11	12
Forecasted demand [MW]	36.76	39.88	42.02	44.34	46.4	48.26
Standard deviation [MW]	4.57	5.01	6.32	8.45	3.24	3.79
Market price [$/MWh]	29.44	30.79	34.97	38.52	43.33	46.3
Stage	13	14	15	16	17	18
Forecasted demand [MW]	48.95	49.8	49.95	50	49.72	48.54
Standard deviation [MW]	6.28	2.52	9.36	3.62	4.01	7.68
Market price [$/MWh]	48	51.4	52.83	53.91	50.83	48.8
Stage	19	20	21	22	23	24
Forecasted demand [MW]	47.51	46.13	45.57	44.56	41.58	37.76
Standard deviation [MW]	4.38	3.4	3.73	4.79	3.61	1.9
Market price [$/MWh]	43.09	39.26	38.65	37.43	32.21	30.56

6.2 Simulation Results

The simulated daily operating cost of each case is listed in Table 6.2 and the corresponding reserve band capacity and calculated MIP for each stage are listed in Table 6.3. With MG-A, the operating cost with this paper's method was reduced by 20.77% compared with Method I and 6.34% compared with Method II. With MG-B, the operating cost with this paper's method was reduced by 31.13% compared with Method I and 4.47% compared with Method II.

Table 6.2 Expected value of total operating cost of MG-A and MG-B according to the determination of reserve band capacity for Microgrid Islanding Rule B

	MG-A	MG-B
Method I	$ 81,511	$ 157,284
Method II	$ 68,950	$ 113,385
Method III	$ 64,582	$ 108,319

Table 6.3 Optimal band capacity and MIP values of the six cases for Microgrid Islanding Rule B

Stage		1	2	3	4	5	6	7	8	9	10	11	12
	Case I-A/B	7.14	6.72	6.50	6.34	6.40	6.66	7.22	7.74	8.21	8.62	9.08	9.40
Band	Case II-A	8.47	11.50	7.16	11.02	7.52	11.31	11.63	21.22	25.61	20.89	12.38	11.94
capacity	Case II-B	13.06	17.48	10.14	16.37	11.90	14.48	18.91	25.51	28.48	21.94	12.65	12.76
[MW]	Case III-A	5.38	6.78	4.28	7.63	4.41	6.13	8.54	11.92	14.14	10.73	6.37	6.78
	Case III-B	7.03	8.69	5.19	9.62	5.69	8.27	11.04	13.96	15.70	11.66	6.77	7.09
	Case I-A/B	0.0249	0.0721	0.0905	0.1153	0.1275	0.0992	0.1082	0.1768	0.2630	0.2348	0.1318	0.0858
	Case II-A	0.0248	0.0632	0.0770	0.0790	0.0786	0.0785	0.0786	0.0786	0.0785	0.0785	0.0785	0.0785
MIP	Case II-B	0.0250	0.0640	0.0781	0.0801	0.0796	0.0791	0.0791	0.0791	0.0791	0.0790	0.0788	0.0787
	Case III-A	0.0317	0.0817	0.0967	0.0966	0.0960	0.0967	0.0984	0.0927	0.0855	0.0815	0.0798	0.0792
	Case III-B	0.0248	0.0632	0.0770	0.0790	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785

Table 6.3 Optimal band capacity and MIP values of the six cases for Microgrid Islanding Rule B

Stage		13	14	15	16	17	18	19	20	21	22	23	24
Band capacity [MW]	Case I-A/B	9.67	9.86	9.91	9.98	10.00	9.90	9.56	9.26	9.25	8.97	8.13	7.43
	Case II-A	16.48	30.50	15.54	28.22	16.40	31.83	17.53	14.19	15.09	22.69	12.73	7.66
	Case II-B	15.02	30.27	15.70	30.33	17.01	33.08	18.84	15.42	16.45	21.63	18.87	13.47
	Case III-A	8.45	16.28	8.58	16.11	8.49	17.33	9.43	7.18	7.70	11.08	7.56	4.91
	Case III-B	8.85	17.21	8.95	16.90	8.84	18.38	10.08	7.65	8.28	12.76	9.64	7.05
MIP	Case I-A/B	0.0775	0.1301	0.1577	0.1510	0.1496	0.1768	0.1957	0.1191	0.0842	0.0887	0.0979	0.0883
	Case II-A	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0786
	Case II-B	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785
	Case III-A	0.0790	0.0793	0.0794	0.0794	0.0795	0.0795	0.0797	0.0794	0.0794	0.0803	0.0854	0.1094
	Case III-B	0.0787	0.0788	0.0789	0.0789	0.0790	0.0790	0.0790	0.0788	0.0788	0.0788	0.0790	0.0794

Since the MGO of Method I just prepared a constant ratio reserve capacity and did not consider the market and grid condition, such as market price, generation cost, and uncertainty of demand, it may prepare an excessive or insufficient reserve capacity most of the time. In other words, this MGO sometimes paid too much cost in hedging the risk of expensive island operation, or sometimes took the islanding risk too much. Table 6.3 shows that the MIP values of MGO of Method I change greatly. On the contrary, MGOs of Method II and III predicted the stochastic island operation based on the uncertainty modeling, and determined their reserve capacity considering the market and grid condition. Therefore, these two MGOs have relatively small and constant MIP values and reduce their operating cost. However, there is a big difference in predicting the probability of microgrid islanding between Method II and III. MGO of Method II thought that an islanding event always occurred when it violated its reserve band contract, whereas an islanding event in Method III might not occur depending on the system condition even if the MGO violated the contract. As mentions in Section III, the island operation of a microgrid cannot be caused by the simple logical condition like the breach of a band contract, and there are various points to be considered before triggering islanding. Therefore, measuring the risk of island operation by Method III is reasonable, and Method II tends to overstate the risk. As a result, the operating costs by Method III is smaller than the operating costs by Method II, although MIP values during 24 stages by Method III are always larger than the MIP values by Method II. To be specific, Case III-A decrease band purchase cost by $5,206 compared with Case II-A whereas the increase of expected islanded operating cost caused by the increase of MIP is just $669. Similarly, the reduced band purchase cost and increased expected islanded operating cost are relatively

$5,891 and $392 for MG-B. In other words, Method III lessens the worry about the probability of island operation to a reasonable level, and enables to hedge the islanding risk efficiently.

Islanding probability function, g_{ij}, enables to reflect the expected islanded operating cost that would vary depending on the market and grid conditions, and this is the reason that the operating costs by Method III are smaller than the operating costs by Method I and II. Therefore, considering that g_{ij} reflects these external conditions of microgrid, its influence on the reserve operation and operating cost of the microgrid can be studied by varying the coefficients of function. In other words, this simulation section will give some intuition about how MGO can cope with the change of the external condition (g_{ij} function). Below simulations were done only for the 1st stage of MG-A and MG-B to clarify the relationship between band operation strategy and each coefficient of g_{ij}. Two coefficients of g_{ij} were selected for the analysis. First, b in (5-11), which is related with the speed of islanding probability increase when MGO violate the band contract, was varied from 1.5 (fast increase) to 10 (slow increase). With this, penalty price was varied from the 100% value of energy price to the 200% value of energy price. And other coefficients, a and C, are fixed as 10 and 0.01, which are the same with the value of the original simulation setting subsection. Figure 6.1 shows the variation of the simulation settings.

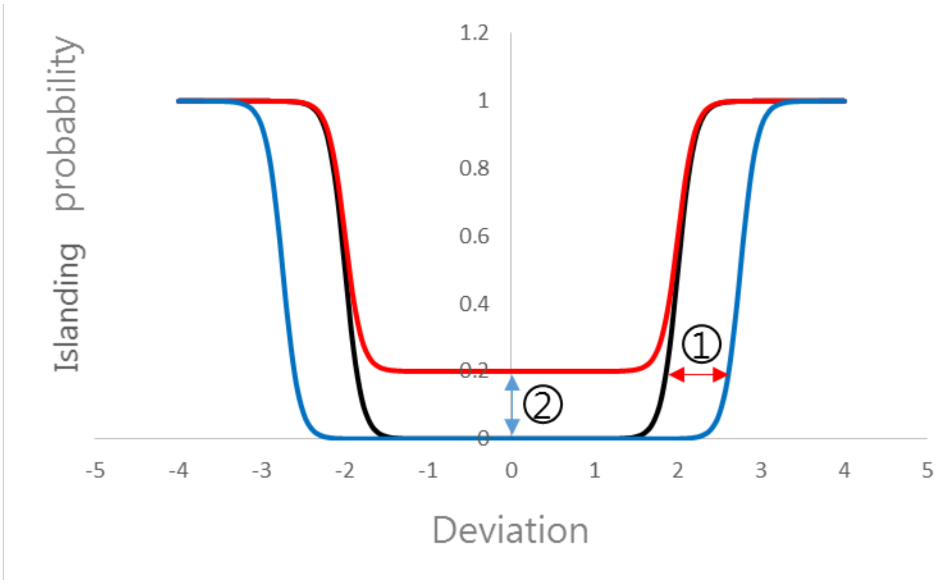

Figure 6.1 Variation of the microgrid islanding probability function for sensitivity analysis

Table 6.4 Sensitivity analysis I with coefficient b and λ_i^{PG}

b \ λ_i^{PG}	0%	25%	50%	100%	b \ λ_i^{PG}	0%	25%	50%	100%
1.5	1.30	1.30	1.30	1.30	1.5	1.26	1.26	1.26	1.26
2	1.00	1.00	1.00	1.00	2	1.00	1.00	1.00	1.00
3	0.69	0.69	0.69	0.69	3	0.71	0.72	0.72	0.72
4	0.53	0.53	0.53	0.53	4	0.57	0.57	0.57	0.58
5	0.43	0.43	0.43	0.44	5	0.47	0.48	0.49	0.50
10	0.24	0.25	0.26	0.29	10	0.30	0.33	0.36	0.41

Table 6.4 shows the simulation results, and the determined reserve band capacities were normalized with the original setting result ($b = 2$, $\lambda_i^{PG} = 125\%$) for easy comparison. The results represent that band operation is sensitive to the change of b in both MG-A and MG-B. This is because MGO can hedge the risk of islanding with relatively small band purchase cost as the increase of makes the islanding probability decrease with the same band capacity. Since either MG-A or MG-B has expensive islanded operating cost compared to the relatively cheap grid-connected operating cost, great influence of b on the MGO's reserve operation is reasonable. For the similar reason the band operation is insensitive to the change of λ_i^{PG}, since the portion of penalty cost in total operating cost is very small. The influence of change of penalty price increases a little bit when b has a large value (slow increase). This is because the portion of penalty cost increase in this case, since large b enables MGO to have a small MIP value with small band purchase cost. Similarly, MG-A is more sensitive to the change of penalty price than MG-B, because it has relatively small islanded operating cost.

Next the coefficient C in (5-11), which is the islanding probability related with Rule III, is varied from 0 to 0.1. Table 6.5 shows the optimal reserve band capacities and corresponding MIPs and operating costs. Band capacity decreases as C increase in Table 6.5, even though the values of MIP and operating cost increase. This is because the portion of islanding risk, which MGO can hedge with reserve band operation, decreases when C increase. In other words, MGO regards the islanding as an inevitable event as C increase. Therefore, the optimal reserve band capacity is 0 for the extreme case where $C = 1$. However, it is checked out that the influence of C on MGO's operation strategy is negligible in the region of realistic C value (around or smaller than 1%). Since the islanding caused by the coefficient C is a kind of accidental event such as line fault or malfunction of circuit breaker, it is reasonable. Analytically, this is because the change of C affects only on the value of MIP, but not on the slope of MIP with respect to reserve band, $\frac{\Delta MIP}{\Delta BD}$, in this low C region. Therefore, the change of C nearly does not affect both increase of band purchase cost for the MIP decrease and decrease of islanded operating cost from the MIP decrease in this region. Therefore, the operation strategy that purchasing additional reserve band to decrease the islanding risk in response to the increase of C is inefficient. Difference between the MIP values of MG-A and MG-B in Table 6.5 represents that the slope of MIP with respect to reserve band is nearly constant in the low C region.

Above two analyses represents that MGO's operation strategy may or may not be affected by the model of g_{ij} depending on the operating condition. Therefore, MGO has to model g_{ij} function for the reliable reserve operation, considering the sensitivity from modeling error.

Table 6.5 Sensitivity analysis II with coefficient C

	C	Reserve Band	MIP	Cost	
MG-A	0	4.70	0.0230	1197	
	0.001	4.69	0.0255	1198	
	0.005	4.69	0.0352	1204	
	0.01	4.69	0.0472	1211	
	0.02	4.69	0.0709	1225	
	0.05	4.68	0.1392	1267	
	0.1	4.66	0.2441	1330	
	C	Reserve Band	MIP	Cost	$\frac{\Delta MIP}{\Delta BD}$
MG-B	0	4.70	0.0230	1197	0.0117
	0.001	4.69	0.0255	1198	0.0116
	0.005	4.69	0.0352	1204	0.0115
	0.01	4.69	0.0472	1211	0.0113
	0.02	4.69	0.0709	1225	0.0111
	0.05	4.68	0.1392	1267	0.0103
	0.1	4.66	0.2441	1330	0.0090

Chapter 7. Conclusions and Future Extensions

7.1 Conclusions

The advent of distributed energy resources (DERs) in the power system, which were not worthy of using in the real world due to their low efficiency compared to the large synchronizing machine, has been concerned with imposing the undue burden on the system operator and impeding the reliability and efficiency of system operation. To solve this problem, the microgrid concept was appeared and many researches has been developed until now.

This dissertation focuses on the island operation of a microgrid. In other words, this dissertation have described a method of taking the risk of microgrid island operation into consideration when the microgrid system operator (MGO) makes a decision in the scheduling level. In addition to this, an index called the microgrid islanding probability (MIP) was defined, and a probabilistic model was composed based on the MIP to describe microgrid islanding. To make a quantitative analysis, a market structure was postulated as a mandatory market for the microgrid, which was suitable for the decentralized operation in the multi-microgrid environment. Postulated market was Power Exchange for Frequency Control market, which was devised by Ilic *et al*. and consisted of energy market and reserve band market. For the application of the proposed method to the PXFC market, two microgrid islanding rules were proposed as market rule in the PXFC market. In addition to this, a method of determining the optimal reserve capacity have been investigated, taking into account microgrid islanding and penalties under the PXFC market environment. After composing some penalty rules for microgrid islanding, the optimal band capacity was formulated analytically as an optimization problem with an objective that minimizes the operating costs. The effectiveness of the proposed method in terms of the operating cost was investigated via a comparison with the other methods using numerical simulations. The simulation results suggest that it is favorable for a microgrid to operate with a high risk of islanding if the generation capability within the microgrid is large, or if the market prices for the reserve band capacity are high. And the hysteretic characteristics of island operation is revealed by the optimal reserve band capacities and the MIP values.

In conclusion, MGO will take more active and large roles in the system operation than traditional distribution network under the paradigm of decentralized operation with multi-microgrid system. For example, demand forecasting and energy resources scheduling will be independently conducted by MGO. In these decision making process, MGO has to take into the island operation that has great effect on its grid. This dissertation proposed a method of enabling MGO to reflect the risk of microgrid island operation in terms of operating cost during the scheduling level. Therefore it is significant and meaningful to do the research on the optimal operation of a microgrid.

7.2 Future Extensions

Using the proposed method, MGO can develop the optimal reserve operation strategy depending on the market and grid conditions. Nevertheless, further research is necessary for more effective implementation and application of the proposed scheme in a real-world application. First, proposed probabilistic analysis based on MIP can be applicable to other system scheduling researches, since it enables MGO to take the risk of uncertain island operation of a microgrid into account. However, this dissertation just applied it to a simple operation scheduling case for verifying the effectiveness of the proposed method. Therefore, other scheduling researches, such as ESS scheduling or unit commitment of a microgrid, can make a good use of the proposed method.

Second, the proposed method needs to be extended to cope with various types of electricity market structure other than the PXFC market in this paper. Although the PXFC market in this paper was an inevitable choice, since there was no market structure that deals with the island operation of a microgrid, it is just a hypothetical market structure. Therefore, it would be much helpful to implement the proposed method, if the analysis of this dissertation is applied to an existing market structure. Next, an elaborate modeling of islanding probability function, g_{ij}, which was newly defined in this dissertation, is necessary for MGO's optimal operation. Although it was assumed that islanding probability function is given here, there should be additional researches about g_{ij} modeling itself as the uncertainty model. Lastly, the distribution of responsibility for the microgrid islanding event needs to be complemented. Although Rule A-IV and Rule B-VI defined the responsibility problem, it was just a simple case and there could be many other cases for the contract by contract. Therefore, referring to the Appendix C, additional analysis for this problem is necessary.

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Appendix A

Common Definition of Microgrid

Although Introduction Section searched the definition of microgrid and various previous researches of it, it is still hard to find a widely used and common definition of microgrid. Therefore this appendix will look for each definition of microgrid from several major references, and find things in common in these references. Based on this, general component of a microgrid and objective function of microgrid operation will also be examined in this appendix.

First, the United States Department of Energy and the Electric Power research Institute defined microgrid as follows: Microgrid is 1) a group of interconnected loads and distributed energy resources within clearly defined 2) electrical boundaries that 3) acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to 4) operate in both grid-connected or “island” mode [36]. Second, Nikos Hatziargyriou, *et al.* defined microgrid as follows: microgrid is a local control cluster of distributed energy resources, such as gas turbines, fuel cells, combined heat and power plant, and wind turbines in distribution network (usually under 69kV) [1]. Therefore, microgrid will be regarded as a single generator or load by the main grid, and enable to reduce the control burden of the main grid. Next, Robert H. Lasseter, *et al.* defined microgrid as follows: Microgrid is a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area [2].

From the above references, commonly a microgrid is a subsystem consisting of local demand and distributed energy resources, and has a control center which dispatches distributed resources. And microgrid can take an island operation when there is an accident in the main grid that can impede its reliable energy supply. Also microgrid can sometimes supply not only electricity demand but also heat demand.

Appendix B

Pattern Search Optimization

The optimization problems in (3-1) and (5-1) can be solved using an optimization algorithm, which may either be an iterative method or a heuristic method [23]. The resulting optimal frequency control band requested in the PXFC market and the corresponding minimum operating cost can be obtained. The simulations in this dissertation are performed with MATLAB R2013b, and the optimization problems are solved by the pattern search algorithm. The pattern search algorithm is a numerical optimization methods that do not need to calculate the gradient of the objective function. Therefore, it is useful for the optimization problem case that has a discontinuous or indifferentiable objective function. Figure B.1 shows an example of iteration process of the pattern search algorithm.

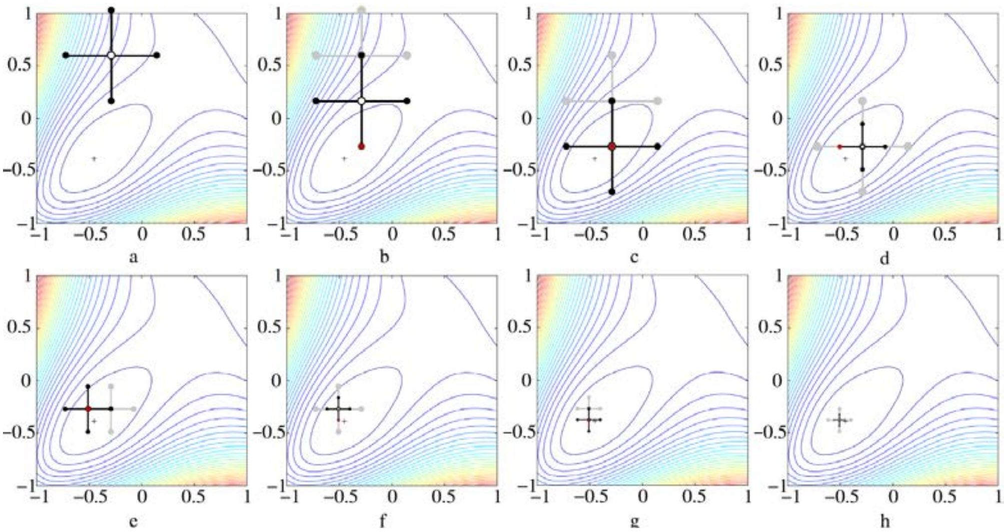

Figure B.1 Iteration example of a pattern search algorithm [37]

Appendix C

Damages for Breach of Contract

Distribution of the responsibility about the breach of a contract caused by microgrid island operation was examined in Microgrid Islanding Rule A-IV and Rule B-VI. However, these two rules are just simple example cases, and the responsibility about the breach of a contract in the real world will be defined case by case. This appendix will examine several ways of evaluating the damages for breach of a contract in reference to [29].

I. Substitute-Price

If a party of a contract breaks its promise, the victim may require the promised performance with the substitute performance. This substitute-price awards the victim the value of replacing the promised contract with a substitute performance. For example, a company, named EPNEL, offered computers at the price λ_E and a consumer orders x_{com} computers. Assume that, if EPNEL breaches this contract, the consumer cannot help getting equivalent computers by paying higher price λ_S to SNU. Then the consumer can replace the breached contract with $x_{com} \cdot (\lambda_S - \lambda_E)$. In this case, $x_{com} \cdot (\lambda_S - \lambda_E)$ is the expected money that will be awarded as damages of the contract for the consumer by EPNEL.

II. Lost-Surplus

The lost-surplus doctrine awards the victim of the contract breach the surplus that the victim would have enjoyed if the breaching party had performed the contract. For example, if EPNEL purchase a computer from the wholesale market at the price of λ_W, and if the consumer promised to purchase x_{com} computers at the price of λ_E, then EPNEL would have enjoyed $x_{com} \cdot (\lambda_E - \lambda_W)$. This amount of money can be awarded to EPNEL for the damages of the breached contract.

III. Opportunity-Cost

The opportunity-cost doctrine awards the victim of the contract breach the opportunity cost that the victim would have enjoyed if he had signed the best alternative contract. For example, assume that there was another computer retailer, named MISLAB, who offered computers to the consumer at the price of λ_M. Then, the consumer forgave the opportunity of purchasing x_{com} computers at the price of λ_M. Therefore, $x_{com} \cdot (\lambda_E - \lambda_M)$ is the amount of money that EPNEL would pay to the customer as the opportunity-cost.

IV. Diminished-Value

Unlike the above three cases, a contract can be partial or imperfect. Then, the promised value of the contract will be decreased. In this case, the diminished-value doctrine awards the victim the difference between the original value and decreased value. For example, assume that originally EPNEL promised the customer to sell computers with 20 inches monitors a market value of λ_{20}. However, EPNEL delivers computer with 19inches monitors a market value of λ_{19} to the customer. Then, $x_{com} \cdot (\lambda_{20} - \lambda_{19})$ is the amount of money that EPNEL would pay to the customer as diminished-value.

V. Out-of-Pocket-Cost

The out-of-pocket-cost doctrine awards the victim of the contract breach the difference between the reliance cost prior to the breach, and the value produced by the reliance cost after breach. For example, assume that EPNEL breached an agreement to sell x_{com} computers at the price of λ_E. In reliance on the contract, the customer purchased x_{com} desks from DeskWorld at the price of λ_D. After EPNEL breaches, the customer's out-of-pocket cost is equal to the cost of cancelling the desk purchase contract.

Appendix D

Reserve Scheduling of a Microgrid Considering Market Participation and Energy Storage System

As mentioned in the Future Extensions in Section 7.2, the method proposed in this dissertation can be applicable to other system scheduling problems. Appendix D is a summary of [38], which was published by the author, and have the same objective as this dissertation that minimizing the operating cost of a MGO under PXFC market environment. [38] did not take the island operation of microgrid into account, but take the ESS scheduling with reserve market purchase into account. Later, this dissertation's method based on MIP will be applied to this ESS scheduling problem.

VI. Optimal Operation of ESS in the Energy Market of PXFC

Mathematical models for ESS operation are selected from [39] to analyze the operation cost and the sequential quadratic programming (SQP) method is applied to achieve the maximum benefit. Used model and assumptions are described in the following.

A. ESS Model and Assumptions

If the output power of ESS is selected as a state variable, then the stored energy could be calculated from the sum of that output power. Since it is generally assumed that hourly spot price is given, time step used in the operation of ESS is one hour. The stored energy can be expressed as

$$
\begin{cases} E_{t+1} = E_t + \eta P_t \text{, when charging} \\ \\ E_{t+1} = E_t + \eta P_t \text{, when discharging} \end{cases} \qquad \text{(D-1)}
$$

where P_t is the output power of ESS at hour t, η is the efficiency of charging/discharging, and E_t is the stored energy in ESS at hour t. Some assumptions related with the ESS are below.

(i) There are maximum charging/discharging power and maximum energy capacity of ESS.

$$-P_{\max} < P_t < P_{\max} \qquad \text{(D-2)}$$

$$0 < E_t < E_{\max} \qquad \text{(D-3)}$$

(ii) The stored energy in the ESS at 00:00 hour is the same with the stored energy at 24:00 hour.

$$E_0 = E_{24} \qquad \text{(D-4)}$$

(iii) The hourly system price is not changed by the operation of the ESS (price taker).

B. Problem Formulation

Since the hourly day-ahead system price is given, MGO can decide the charging schedule in order to maximize the profit. The profit in a day can be calculated as follows

$$PF(P_{\max}) = \sum_{t=1}^{24} P_t \cdot \lambda_{DA_t} \tag{D-5}$$

where PF is the profit of the ESS, and λ_{DA_t} is the given hourly day-ahead price. Therefore, the objective function for the maximum profit scheduling of ESS can be written as

$$\max\left\{PF(P_{\max})\right\} = \max_{P_t}\left(\sum_{t=1}^{24} P_t \cdot \lambda_{DA_t}\right). \tag{D-6}$$

VII. Optimal Operation Strategy Considering both Band Capacity and ESS Capacity

MGO could get the profit by ESS scheduling, as considering the hourly system price. However, ESS also could have a role of reserve band in the PXFC market and this could decrease the band cost and expected penalty cost. Therefore, MGO should determine the optimal participating ratio of ESS between energy market and frequency control market as below

$$\left\langle \begin{aligned} P_{bid} &= \alpha \cdot P_{\max} \\ P_{bd,ESS} &= (1-\alpha) \cdot P_{\max} \end{aligned} \right. \tag{D-7}$$

where P_{bid} is the ESS capacity of participating in energy market and α is the ratio of it, and $P_{bd,ESS}$ is the ESS capacity of participating in frequency control market. In this case, final objective function can be expressed as follows

$$C_{tot,i}\left(P_{band,i},\alpha\right) = RG_i\left(P_{band,i} + \frac{P_{bd,ESS}}{2}\right) + EG_i\left(P_{bid}\right) \tag{D-8}$$

Final optimal solution of P_{band} and α, or P_{bid} and $P_{bd,ESS}$, can be calculated by differentiate the equation (D-8). However, the solution will have more complex form than equation (D-8), and formulation of this equation is very hard to find any meaning on it. Therefore, iteration between the optimizing method in energy market and reserve band market is utilized to get the optimal solution of P_{band} and P_{bid}. Flow chart of the utilized iteration method, which is based on the bisection method, is represented in Figure A.

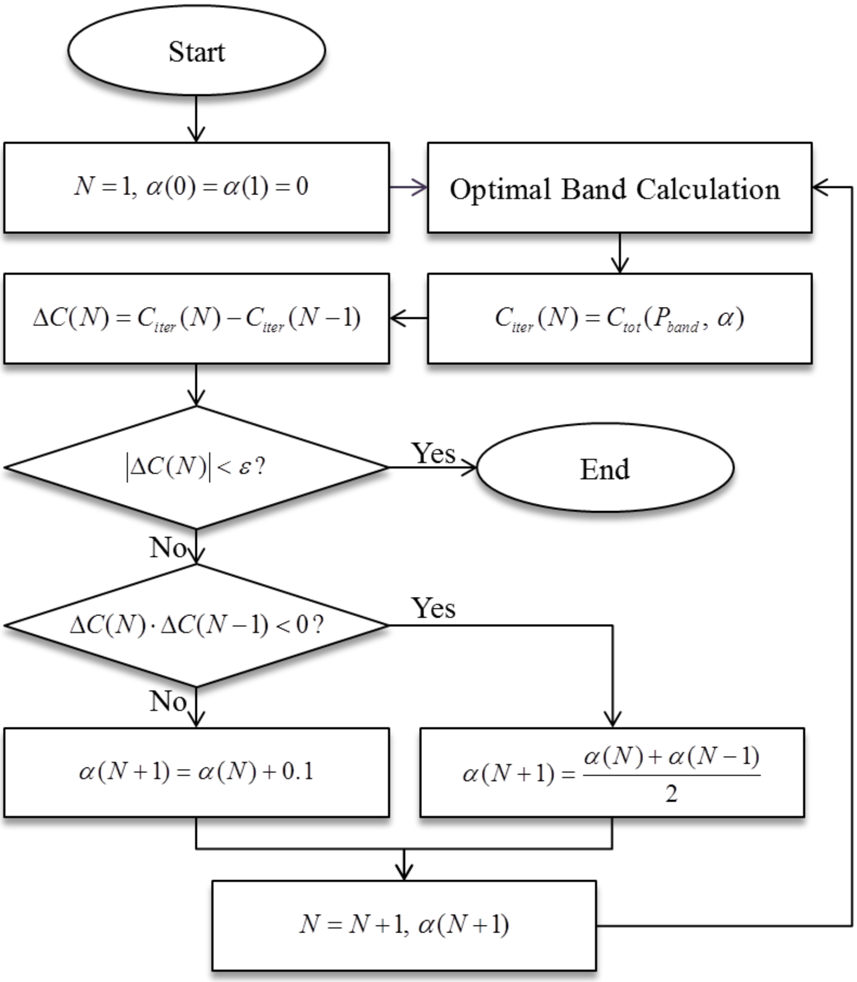

Figure D-1. Flow chart of the iteration method for the optimization

초 록

시장환경에서 마이크로그리드 계통연계 상태의 확률론적 분석에 기반한 최적 예비력 스케쥴링에 관한 연구

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Microgrid는 신재생 에너지원 및 에너지저장장치, 열병합발전과 같은 다수의 분산전원들이 존재하는 전력 시스템의 효율적, 안정적인 운영을 위한 하나의 해결책으로 제시되고 있다. 이러한 Microgrid의 특징 중 하나로 외부 사고에 대응하여 자발적인 독립운전을 수행하여, 내부 수요에 대한 신뢰도를 높일 수 있다는 점이 있다. 하지만, Microgrid가 무한정 에너지원을 보유할 수는 없기 때문에, Microgrid 운영자는 독립운전 수행 시 어쩔 수 없이 부하차단과 같은 조치를 취할 수 밖에 없다. 따라서, Microgrid 운영자는 보유한 에너지원을 운영하는데 있어 이러한 독립운전 상황을 고려하여야만 한다. 이러한 이유로 Microgrid 운영과 관련된 많은 선행연구들이 독립운전을 대비한 예비용량의 스케쥴링을 포함

하고 있다.

본 논문은 Microgrid 독립운전의 리스크(risk)를 분석하여, 계통 운영계획 수립 시 이를 확률론적으로 반영하는 방법론을 제시하였다. 이를 위해 Microgrid의 독립운전을 계약 측면에서 거래의 중단으로 해석하고 거래중단의 책임을 분배할 수 있도록 시장규칙의 형태로 제안하였다. 시장규칙에 따른 영향력을 정량적으로 살펴보기 위해, M. Ilic와 동료들이 제안한 Power Exchange for Frequency Control (PXFC)시장의 시장규칙을 기본으로 서로 다른 두 개의 Microgrid 독립운전 시장규칙을 가정하였으며, 이를 바탕으로 Microgrid 독립운전의 리스크를 분석하였다. 구체적으로 Microgrid 독립운전의 발생상황을 모델링하였으며, 이를 이용해 단위 시간 동안 독립운전이 지속될 확률을 나타내는 Microgrid 독립 확률 (Microgrid Islanding Probability, MIP)를 정의하고 이를 계산하는 방법을 살펴보았다. 새로이 제안된 MIP를 이용하여 Microgrid의 독립운전 리스크를 포함하는 일간 운영비용의 기대 값을 목적함수로 하며 Microgrid 운영자가 PXFC 시장에서 구매하는 시간별 예비용량을 결정변수로 하는 최적화 문제를 수립하였다.

정식화된 최적화 문제는 미국 PJM 시장의 정보를 바탕으로 시뮬레이션을 구성하였으며, 시뮬레이션을 통해 제안한 방법론을 이용한 Microgrid의 예비용량 스케쥴링이 기존의 다른 예비용량 스케쥴링 방법론에 비해 비용측면에서 효과가 있음을 확인하였다. 또한, 시뮬레이션의 MIP 결과를 분석하여 Microgrid 독립운전 발생에 이력현상(hysteresis)이 있음을 확인할 수 있었다. 제안한 방법론을 활용한다면

Microgrid 운영자는 시장과 계통 상황에 따라 변화하는 최적 예비용량 스케쥴링을 수행할 수 있다.

주요어 : Microgrid, 독립운전, 베르누이 시행, 예비력, 비용 최소화, 전력시스템 운영
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